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Study 26

Gold Exploration in the Timmins Area

Using Field and Lithogeochemical Characteristics of Carbonate Alteration Zones

by

J. Andy Fyon and J.H. Crocket

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FOREWORD

GOLD EXPLORATION IN THE TIMMINS AREA

Carbonate alteration zones are mineralized. This report represents the results of a study to determine: the field, petrographic, and geochemical characteristics of both mineralized and barren carbonate alteration zones; an hypothesis of their origins, and suggests lithogeochemical methods for distinguishing between them. These have direct application to exploration for carbonate-hosted gold deposits.

E.G. Pye
Director
Ontario Geological Survey

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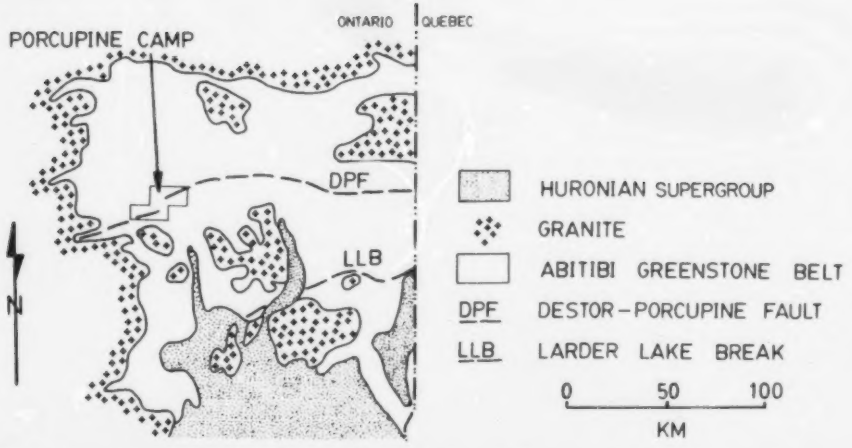

Figure 1 –Location of the Porcupine gold camp within the Abitibi Greenstone Belt (after Goodwin and Ridler 1970).

ABSTRACT

All gold deposits within the Early Precambrian Tisdale Group of the Timmins area are spatially associated with carbonate alteration zones; however, not all carbonate alteration zones host gold mineralization.

Discordant and stratabound carbonate alteration zones occur throughout the stratigraphy within the komatiitic and magnesium tholeiitic volcanic rocks at the base of the Tisdale Group. The alteration zones consist of an inner assemblage of ferroan dolomite, quartz, and trace chlorite and sericite which is sequentially enveloped by calcite-quartz and chlorite-rich subzones. Factors which control the distribution of carbonate alteration include; joint systems, flow contacts, synvolcanic faults, and the bulk composition of the host rock. Ultramafic komatiitic flows are more readily and extensively carbonatized than adjacent felsic or basaltic rocks.

Carbonate alteration took place at the sea floor/sea water interface and took place within the volcanic pile in a subsea floor environment. Insignificant gold production has come from the subsea-floor alteration environment. On the other hand, sea floor alteration zones, which represent regions of hydrothermal fluid discharge into the hydrosphere, are spatially associated with felsic volcanic complexes and with syngenetic, auriferous, cherty dolomite mineralization.

Carbonatized, magnesium tholeiitic basalts which host the auriferous, cherty-dolomite mineralization are enriched in antimony (>0.35 ppm), boron (>30 ppm), gold (>5 ppb), and lithium (>30 ppm) but are depleted in copper (<70 ppm) with respect to carbonatized basalts not associated with gold mineralization. Ore-related, altered komatiitic flows can be screened using gold (>5 ppb), lead (>10 ppm), arsenic (>70 ppm) and antimony (>1 ppm).

The field, petrographic, and lithogeochemical characteristics of the carbonate alteration zones suggest that the hydrothermal fluid was possibly of sea water origin.

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CONVERSION FROM SI TO IMPERIAL			CONVERSION FROM IMPERIAL TO SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 02	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.308 0	cubic yards	1 cubic yard	0.764 555	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 908 8**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

1 ounce (troy)/ton (short)	20.0	pennyweights/ton (short)
1 pennyweight/ton (short)	0.05	ounce (troy)/ton (short)

NOTE–Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries published by The Mining Association of Canada in co-operation with the Coal Association of Canada.

Gold Exploration in the Timmins Area Using Field and Lithogeochemical Characteristics of Carbonate Alteration Zones

by

J. Andy Fyon[1] and J.H. Crocket[2]

INTRODUCTON

Location

The Porcupine Camp, located in the Early Precambrian (Archean), Abitibi Greenstone Belt near Timmins, Ontario (Figure 1), has been an important producer of gold. In total, 32 mines, of which seven properties are currently in operation (Figure 2), have produced approximately 1.6×10^9g (53×10^6 ounces) of gold. The city of Timmins, situated in Tisdale Township, is located at Latitude 48°30′N and Longitude 81°15′W, and is accessible by paved Highway 101 and by a spur of the Ontario Northland Railway. Several secondary roads afford access to most of the mining properties in Tisdale, Whitney, and Deloro Townships.

Purpose and Scope of Study

Virtually all gold mineralization in the Porcupine Camp is hosted in, or is spatially associated with carbonatized volcanic rock (Burrows 1924; Hurst 1936; Ferguson *et al.* 1968; Pyke 1975b; Karvinen 1976, 1978a). The presence

[1]Graduate student, Department of Geology, McMaster University.
[2]Professor, Department of Geology, McMaster University.

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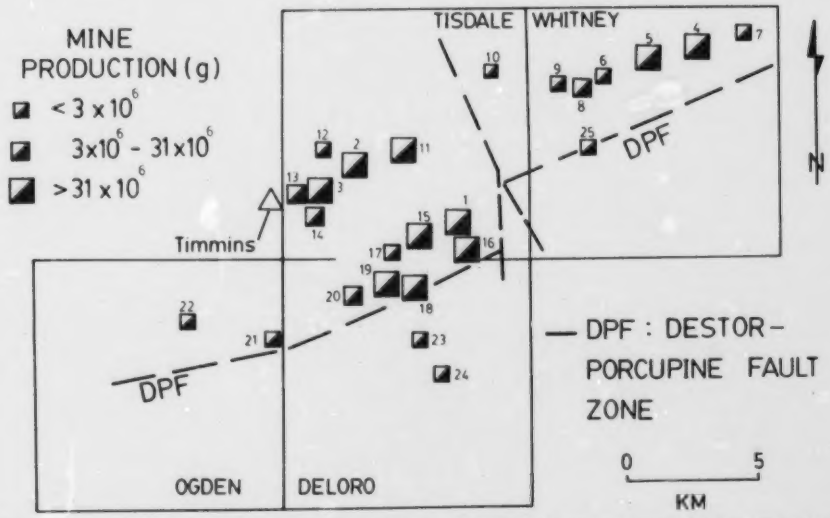

Figure 2–Location of former and presently producing mines, and the Destor-Porcupine Fault Zone in the Porcupine camp. The mining properties* are:

Producing Mines
1 –Dome
2 –McIntyre (Pamour Schumacher property).
3 –Hollinger (Pamour Timmins property).
4 –Pamour #1.
11 –Westfield Minerals (formerly Coniaurum; Pamour option).
19 –Aunor (Pamour #3 Mine).
20 –Delnite.
Former Producers
5–Hallnor.
6 –Broulan Reef.
7 –Hoyle.
8 –Hugh Pam.
9 –Banner Porcupine (formerly Canusa).
10 –Davidson-Tisdale.
12 –Consolidated Gillies Lake.
13 –Moneta.
14 –Vipond.
15 –Paymaster Consolidated.
16 –Preston.
17 –Fuller Claim (Edwards shaft).
18 –Romfield Building Corp. Ltd.
(Buffalo Ankerite Mine: Pamour option).
21 –Kenilworth.
22 –Desantis.
23 –McLaren-Porcupine.
24 –Faymar.
25 –Porcupine Lake.

* For simplicity, the traditional names of mining properties and prospects, as listed by Ferguson *et al.* (1968) and Carlson (1967), are used.

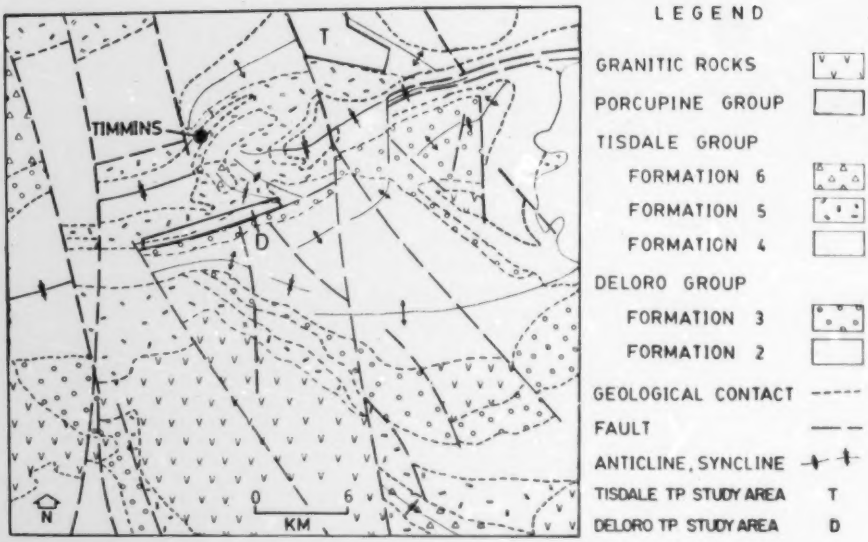

Figure 3–Distribution of volcano-sedimentary rock units in the Timmins area (after Pyke 1975b, 1981, 1982). The Tisdale (T) and Deloro (D) Township detailed study-areas lie at the base of the Tisdale Group.

of carbonate alteration, therefore, constitutes an important exploration tool; however, not all zones of carbonate alteration are host to gold mineralization (Burrows 1924; Dunbar 1948). Hence, it is fundamentally important for a gold explorationist to be able to discriminate between metalliferous and barren carbonate alteration zones. To this end, a geological and geochemical investigation of the carbonate alteration in the Timmins area was initiated in 1977 by the Mineral Deposits Section of the Ontario Geological Survey (Robertson 1977; Fyon and Karvinen 1978; Fyon and Crocket 1979). This work was undertaken in collaboration with the Department of Geology, McMaster University, as a follow-up to the preliminary investigations of W.O. Karvinen (1976).

The objectives of the study were;

1) To better define the nature of the carbonate alteration, including those factors which controlled its distribution,

2) To establish geological and geochemical screens which would be used to discriminate between metalliferous and barren carbonate alteration zones.

Methodology

The approach in this study has been to map in detail at a scale of 1:1200, two control areas (Figure 3). One area hosts mineable gold deposits, the Deloro Township study-area, and the other area hosts only gold prospects, the Tisdale

Township study-area. The purposes of this work were to establish the distribution and stratigraphic relationships of the alteration types present.

The volcanic rock classification used here follows that of L.S. Jensen (1976). The term komatiite, although presently under review (Arndt *et al.* 1979), is used to describe a suite of volcanic rocks ranging in composition from peridotite to basalt, each type having distinctive field and chemical characteristics (Pyke *et al.* 1973; Arndt *et al.* 1977, 1979; Nesbitt *et al.* 1979). The stratigraphic nomenclature is that adopted by Pyke (1975b,1981,1982) and for comparison, earlier stratigraphic subdivisions are given (Figure 4). For convenience, the older names of mining properties and prospects, as listed by Ferguson *et al.* (1968) and H.D. Carlson (1967), are used (*see* Figure 2).

The control areas were selected to permit detailed examination of the lower part of the Tisdale Group where most of the gold mineralization in the Porcupine Camp is apparently restricted (Ferguson *et al.* 1968; Pyke 1975b; Davies 1977; Karvinen 1978a). Both study-areas are characterized by relatively simple structure and both contain carbonate-rich volcanic rock. The felsic volcanic rocks of Formation III (Deloro Group; Figure 4) and the iron-rich (Fe) - tholeiitic basalts of Formation V (Tisdale Group; formerly the Vipond Subgroup of Ferguson *et al.* 1968 and Davies *et al.* 1979) represent two time datums which have been traced throughout the Timmins area (Ferguson *et al.* 1968; Pyke 1975b; Davies *et al.* 1979). These time datums bracket the volcanic rocks of the study-areas, and thus establish the time and stratigraphic equivalence of the study-areas.

Semi-detailed mapping at a scale of 1:6000 was carried out in parts of Whitney, Tisdale, and Ogden Townships (see Figure 2) to confirm and supplement the regional distribution of carbonate-rich rock, as mapped originally by Karvinen (1976, 1978a), and to acquire a regional data base.

Although a number of distinct gold deposit types occur in the Porcupine Camp (compare with Fryer and Hutchinson 1976; Fryer *et al.* 1979; Karvinen 1981), the mineralization within the Deloro Township study-area occurs primarily as a cherty, carbonate-rich exhalative sediment. Furthermore, the rock types sampled for this study were ultramafic to basaltic komatiites and magnesium (Mg)-rich, tholeiitic basalts from Formation IV of the Tisdale Group. Consequently, the conclusions and recommendations of this study apply specifically to this syngenetic ore type and its geological environment. Because of the presence of this type of ore in the Dome (Fryer and Hutchinson 1976; Roberts *et al.* 1978; Fryer *et al.* 1979), McIntyre (Pamour Schumacher property), and Hollinger (Pamour Timmins property) Mines (Karvinen 1981), certain of the conclusions may be applied in a general way to other deposits in the Porcupine Camp.

Acknowledgments

This project, which constitutes part of a Master of Science Thesis completed by the senior author at McMaster University, was initiated by the Mineral Deposits Section of the Ontario Geological Survey as a follow-up to the initial work by W.O. Karvinen during his employment as Northern (Timmins) Re-

Dunbar (1948)	Ferguson *et al.* (1968)	Pyke (1975b)	Pyke (1981, 1982)
Timiskaming	Timiskaming	Porcupine Group Upper Formation Lower Formation	Porcupine Group Upper Formation Lower Formation
Hoyle			
Tisdale Group	Tisdale Group Latite Breccia, Latite (Krist Fragmental) Gold Center Subgroup Vipond Subgroup Central Subgroup Northern Subgroup (Haileyburian)	Tisdale Group Krist Formation Schumacher Formation Goose Lake Formation	Tisdale Group VI Upper Metavolcanic Formation V Middle Metavolcanic Formation IV Lower Metavolcanic Formation
Deloro Group	Deloro Group	Deloro Group Boomerang Formation Redstone Formation Donut Formation	Deloro Group III Upper Metavolcanic Formation II Middle Metavolcanic Formation I Lower Metavolcanic Formation

Figure 4–Comparison of the stratigraphic nomenclature for rocks in the Timmins area. Most recent classification (Pyke 1981, 1982) is used in this report.

gional Geologist, Ontario Ministry of Natural Resources.

Access to mine properties and to mine maps was graciously provided by Pamour Mines Limited, Schumacher Division. Field work carried out in 1977 and 1978 by the senior author, under the direction of J.A. Robertson (formerly Chief, Mineral Deposits Section) and W.O. Karvinen (formerly Resident Geologist, Sudbury), was supported by the Mineral Deposits Section of the Ontario Geological Survey. Many trace element analyses were performed by the Geoscience Laboratories, Ontario Geological Survey, Toronto.

Additional financial support came from a NSERC research grant to Dr. Crocket, McMaster University, who supervised the M.Sc. Thesis. Some mapping and sampling carried out by the senior author during the 1979 and 1980 field seasons was supported in part, by Grant 49, Ontario Geological Survey, Ministry of Natural Resources.

Able field assistance was rendered by M. Goudreau (1977), W. Haskett (1978), E. Ginn (1979), and C. Kasserra (1980).

GEOLOGY

Timmins Area

Early geological syntheses of the Timmins area geology have been made by A.G. Burrows (1924), W.R. Dunbar (1948), and Carlson (1967). Preliminary geological maps of the Timmins Mining Camp were completed for Deloro Township (Ferguson 1958a,b), Tisdale Township (Ferguson 1960a, 1960b,1960c, 1960d) and Whitney Township (Ferguson 1958c, 1958d). The geology of Tisdale Township and its mining properties have been described by S.A. Ferguson *et al.* (1968). The publication of a regional geological map (Pyke 1974) marked the beginning of a mapping and stratigraphic correlation project of the Timmins-Matachewan areas with the attendant geological reports (Pyke 1975a, 1975b, 1978, 1981, 1982; Pyke *et al.* 1978). Regional structural aspects of the Porcupine Camp have been described by Ferguson *et al.* (1968), J.F. Davies (1977), Karvinen (1978b), and Pyke (1975b, 1981, 1982). Detailed structural studies in the Dome Mine (Roberts 1980; Roberts and Spiteri 1979; Roberts *et al.* 1978) have documented a complex evolutionary history for the Porcupine Syncline, a major structure in Tisdale Township (*see* Figure 3).

Field trip guides of the Timmins area have been written by P.T. George (1967), A.M. Goodwin *et al.* (1972), D.R. Pyke (1975a), and Pyke *et al.* (1978).

Briefly described in this section is the stratigraphy of the Early Precambrian (Archean) lithologies exposed in the Porcupine Camp (see Figure 3) as interpreted by Pyke (1975b, 1981, 1982). An older sequence of volcanic rocks, the Deloro Group (Dunbar 1948), consists of basal komatiitic flows (Formation I; Pyke 1975b, 1981, 1982) which are overlain by calc-alkalic basalts and andesites (Formation II; Pyke 1975b, 1981, 1982) and felsic pyroclastic rocks (Formation III; Pyke 1975b, 1981, 1982). Interbedded within the felsic volcanic rocks, near the top of the Deloro Group, are oxide- and sulphide-bearing ironstones. Most of the Deloro Group, south of Timmins, is confined to a large domal structure (Shaw Dome).

A major change from calc-alkalic to komatiitic volcanism marks the beginning of the Tisdale Group. The lowest formation (Formation IV; Pyke 1975b, 1981, 1982) consists of ultramafic to basaltic komatiitic and magnesium (Mg)-tholeiitic basalt flows which are in turn overlain by iron (Fe)-tholeiitic basalts (Formation V; Pyke 1975b, 1981, 1982). The uppermost volcanic sequence, Formation VI, consists of felsic, calc-alkalic pyroclastic rocks.

Metasediments of the Porcupine Group (Lorsong 1975), consist dominantly of interlayered greywacke, siltstone, and lesser conglomerate, and form part of a turbidite sequence. These rocks are time equivalent to the upper part of the Deloro Group and the entirety of the Tisdale Group (Pyke 1981, 1982).

Ultramafic sills and dikes occurring within the Deloro Group metavolcanics may have acted as magma reservoirs during the eruption of the Tisdale Group komatiitic flows (Pyke 1981, 1982).

Minor, subvolcanic quartz-feldspar porphyry bodies ("QFP") occur within a restricted stratigraphic interval at the base of the Tisdale Group; this suggests that these bodies represent rhyolitic vents (Dunbar 1948) and domes (Davies 1977; Karvinen 1976, 1978a; Davies and Luhta 1978; Pyke 1981, 1982).

An important structural "break", the Destor-Porcupine Fault, which transects the Timmins area, has been traced as far west as the Kukatush area (Milne 1972) and as far east as the Noranda area (Wilson 1962; Gelinas *et al.* 1977). This structure, which has localized clastic sedimentation and some komatiitic volcanism, is interpreted to be a fundamental fracture system which was active in the Early Precambrian crust (Pyke 1981, 1982). North of the fault, in the Timmins area, two periods of folding can be recognized. Original north-trending fold-axes have been refolded about a northeast axis (Pyke 1975b; Davies 1977). The Shaw Dome forms the main structural feature south of the Destor-Porcupine Fault (Pyke 1975b, 1981, 1982).

The tops of the Deloro and Tisdale Groups are dated at 2 725± 2 Ma and 2 703± 2 Ma respectively (Nunes and Pyke 1980).

Study-Areas

The relatively simple structure of the study-areas was an important consideration in their selection. Areas having no large scale faults, that is, thousands of metres in strike length, or no large scale folds, still contain carbonatized rock. An example of such an area is northeast Tisdale Township. It is apparent that large scale structure is not necessarily a prerequisite to the formation and localization of carbonate alteration.

Structurally simple areas were examined in detail to establish an alteration norm. Following these examinations, the influence of structure could be evaluated in more structurally complex terrains. Because of this constraint, much of south-central Tisdale Township, which hosts the McIntyre (Pamour Schumacher property) and Hollinger (Pamour Timmins property) Mines, received only cursory examination (1:15 840 scale) by the authors.

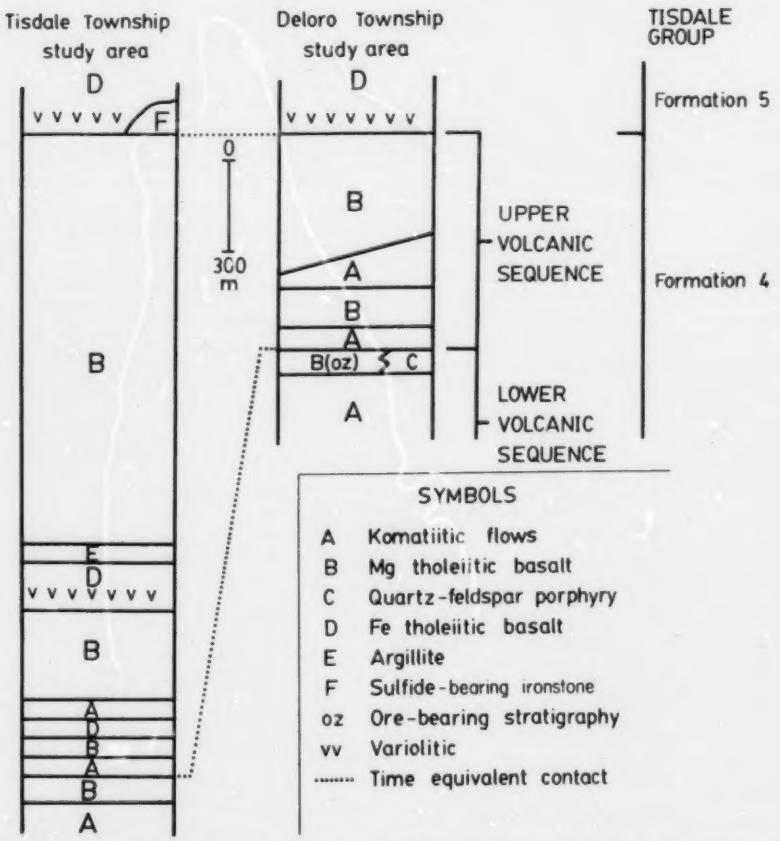

Figure 5–Idealized stratigraphic sections through the Tisdale and Deloro Township study-areas. Group and formation subdivisions are by Pyke (1975b, 1981, 1982). The dotted line joins stratigraphic levels which are inferred to be approximately time equivalent, and is based on regional correlation of lithogeochemically similar rock units.

TISDALE TOWNSHIP STUDY-AREA

Formation IV (Pyke 1975b, 1981, 1982) in this area is subdivided into two sequences based on rock type abundance (Map 1, back pocket; Figure 5). The stratigraphically lowest sequence, herein referred to as the lower volcanic sequence, is dominated by the presence of komatiitic flows interbedded with lesser amounts of Mg-tholeiitic basalt flows. This lower sequence is overlain by Mg-tholeiitic basalt flows which are interbedded with lesser amounts of Fe-tholeiitic basalt and komatiitic flows, collectively referred to as the upper volcanic sequence. The southern limit of the study-area is marked by the contact be-

tween Formations IV and V, above which Fe-tholeiitic basalts predominate.

Only two interflow sedimentary units are exposed. One consists of pyrite-pyrrhotite ironstone, developed intermittently along the contact between Formations IV and V and the other is an argillite which conformably overlies an Fe-tholeiitic basalt unit in the upper lithological sequence (Figure 5). No felsic intrusive or extrusive rocks are exposed in this study-area.

Within the Tisdale Township study-area, east of the Burrows-Benedict Fault, the existence of the North Tisdale Syncline (Ferguson *et al.* 1968; Davies 1977; Davies *et al.* 1979) and the porphyritic latite (Ferguson *et al.* 1968) are refuted by the detailed field and geochemical data reported by J.A. Fyon and W.O. Karvinen (1978), J.A. Fyon (1980a), and J.A. Fyon and J.H. Crocket (1981). The porphyritic latite (Ferguson *et al.* 1968) is a massive, Fe-tholeiitic basalt flow. This stratigraphic section is a south facing, steeply dipping, homoclinal sequence averaging 2800 m in thickness (see Figure 5).

DELORO TOWNSHIP STUDY-AREA

As in the Tisdale Township study-area, Formation IV is subdivided into two sequences. The lowest lithological sequence (Figure 5; Map 2, back pocket) consists predominantly of komatiitic flows, although Mg-tholeiitic basalts and locally volcaniclastic sediments (agglomerate) occur at the top of this sequence. In addition, localized at the top of the lower sequence, are bodies of stratabound quartz-feldspar-sericite schist (QFP) which occur in the Delnite, Aunor, and Buffalo Ankerite Mines. Interbedded within the Mg-tholeiitic and komatiitic flows at the top of the lower lithological sequence, are auriferous, cherty dolomite exhalites (Photo 1), which constitute the main ore material in the Delnite, Aunor, and Buffalo Ankerite Mines.

The base of the upper lithological sequence is marked by a thin, less than 60 m thick unit consisting of komatiitic flows. Above this unit, Mg-tholeiitic basalts occur interbedded with rare chemical (marble) and volcaniclastic (siltstone) sedimentary units. The appearance of abundant Fe-tholeiitic basalt of Formation V, locally variolitic (formerly Vipond Group; Ferguson *et al.* 1968), marks the upper stratigraphic boundary of this study-area.

The major fold structures within the Deloro Township study-area are the Kayorum Syncline and an unnamed east-west trending anticline located north of the Destor-Porcupine Fault (Map 2, back pocket). The stratigraphic thickness of the volcanic section studied in the Deloro Township study-area is approximately 900 m.

CARBONATE ALTERATION

All gold deposits in the Porcupine camp occur within or are proximal to zones of carbonate alteration (Burrows 1924; Hurst 1936; Ferguson *et al.* 1968; Carlson 1967; Pyke 1975b; Karvinen 1978a). Not all zones of carbonate alteration, however, host gold mineralization. A better understanding of the gold

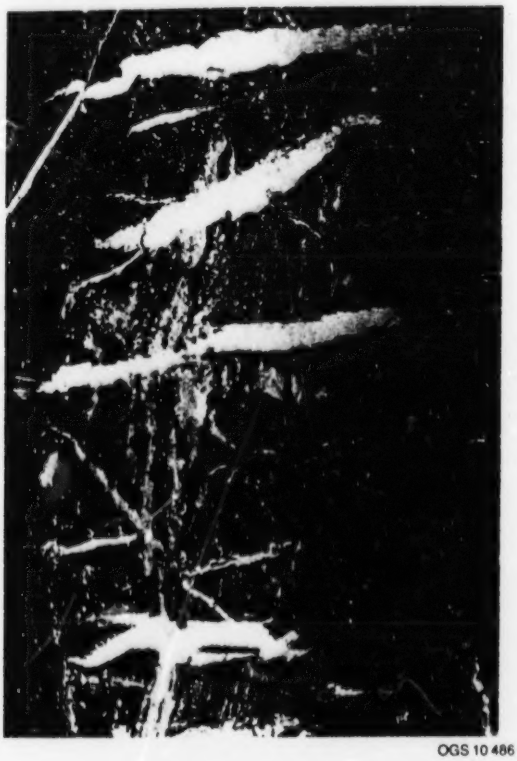

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Photo 1–Stratiform, auriferous, cherty-dolomite, 0.3 m in thickness, exposed on the 1000-foot level of the Aunor Mine (Pamour #3). Transverse, tensional, quartz 'ladder' veins cut across the cherty dolomite, but terminate at the sediment/host rock contact.

metallogeny will be gained by acquiring more knowledge of both the volcanic environment in which the gold deposits occur and the processes which caused the carbonate alteration.

When developed in Mg-tholeiitic basalt, the carbonate alteration zones can be subdivided into three alteration facies (Fyon 1980a; Fyon and Crocket 1981) which are, from the most altered to the least altered:

1) pervasive carbonate
2) transitional
3) chloritic (Figure 6)

The pervasive carbonate zone can in turn be subdivided into an inner dolomite-rich subzone which is surrounded by an outer calcite-rich subzone. In any particular alteration zone, not all alteration assemblages need be present, but in all cases, the relative juxtaposition of the assemblages present remains

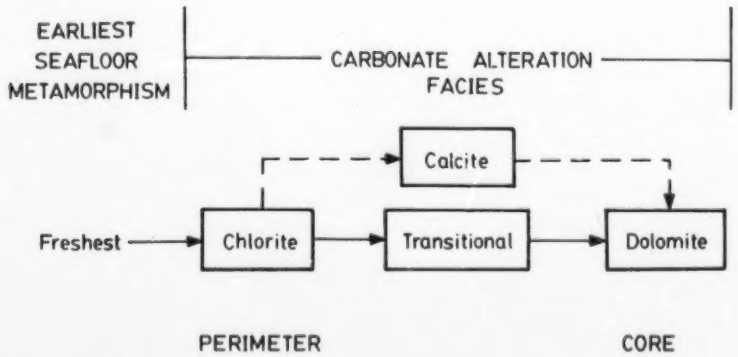

Figure 6–Simplified alteration facies relationship diagram illustrating the observed transitions between alteration facies developed in basaltic volcanic rocks. The arrows indicate increasing carbonate alteration intensity. The dashed lines indicate the predominance of the calcite alteration facies when the transitional and dolomitic facies are not well developed. The earliest sea floor metamorphism is characterized by vesicle filling by clays, zeolites, and chalcedony which have subsequently been replaced by quartz, chlorite, and clinozoisite.

constant. Commonly, the dolomitic carbonate subzone is subordinate and the calcite carbonate domain is predominant, in which case, the transitional alteration facies is not well developed or may even be absent (Figure 6).

Figure 7 shows the mineralogical changes in a Mg-tholeiitic basalt flow as a function of increasing carbonate alteration intensity. Alteration intensity is approximated by the total volatile content of a sample (loss on ignition; LOI). For sulphide-rich samples, oxidation of iron, however, often results in anomalously low or even negative LOI determinations. The use of CO_2 as a crude index of carbonate alteration is less satisfactory, but is often necessary for sulphide-rich rocks. This is because the hydrous alteration facies are reduced in significance owing to their low CO_2 contents which are less than 0.3 weight percent in Mg-tholeiitic basalts.

The proportion of Ca-aluminosilicates (metamorphosed equivalents being tremolite and clinozoisite) decreases with an increasing degree of carbonatization. Sericite appears only after all Ca-aluminosilicates are destroyed. Increasing alteration intensity in the pervasive carbonate zone results in the destruction of quartz, albite, and chlorite with concomitant increase in dolomite (or calcite) and sericite.

Alteration Distribution and Morphology

Zones of carbonatized rock occur throughout the volcanic units of the Tisdale and Deloro Township study-areas as both discordant and stratabound zones (Fyon and Karvinen 1978; Fyon and Crocket 1981; and Maps 1 and 2, back pocket).

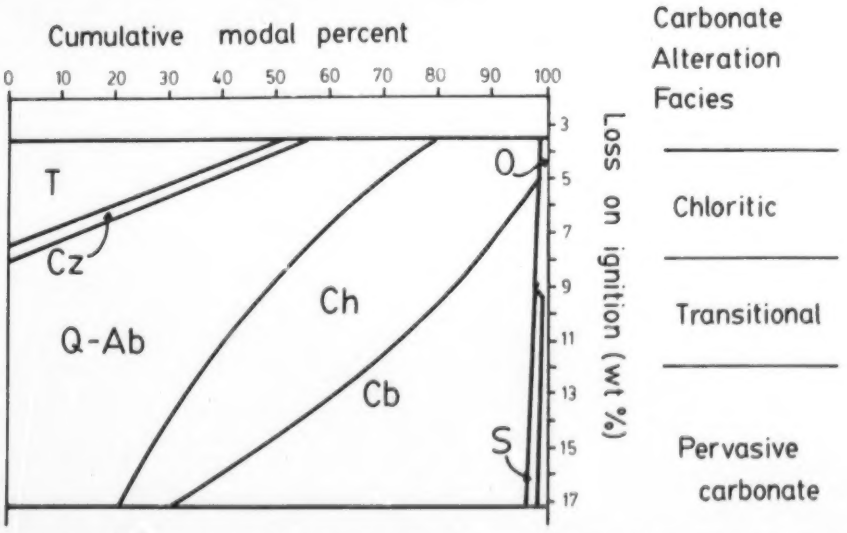

Figure 7–Variation of mineral assemblages in Mg-tholeiitic basalt as a function of carbonate alteration intensity, expressed by loss on ignition. Abbreviations are: T (tremolite); Cz (clinozoisite); Q-Ab (unsubdivided quartz and albite); Ch (chlorite); Cb (carbonate-dolomite or calcite); S (sericite); O (opaques - pyrite, chalcopyrite, sphalerite, leucoxene).

Discordant alteration zones are characterized by alteration assemblage boundaries which trend transverse to the local stratigraphy. For example, on the Davidson-Tisdale property (Figure 8, Chart A, back pocket), in Tisdale Township study-area (Map 1), a discordant carbonate alteration zone cuts across massive and pillowed Mg-tholeiitic basalt flows and dies out gradually in both vertical and lateral dimensions. Zones of chloritic alteration not only envelope the pervasive dolomitic carbonate core, but occur as patches within the dolomite-rich core, indicating that the carbonatization was only locally pervasive. At this locality, the dolomitic-carbonate facies predominates and the calcite-carbonate facies is only weakly developed.

Approximately 6 x 10^4 g (2000 ounces) of gold were extracted from a quartz vein as wide as 5 m, of limited strike length (15 m) and vertical extent (30 m) (Ferguson *et al.* 1968, p. 81). The quartz vein occurs within pervasively carbonatized rock (dolomite facies).

On the Dobell property (Figure 9), a major discordant carbonate alteration zone cuts across the volcanic stratigraphy. At this property, the calcite-carbonate facies is prominent. The dolomitic alteration facies occurs as pods and fingers of restricted strike length, less than 50 m, within the calcite alteration zone. On the east edge of the property, a second, smaller alteration zone consists of a dolomitic core enclosed by a chloritic subzone. The transitional facies (*see* Figure 7) separates the chloritic and dolomitic zones; however, the thick-

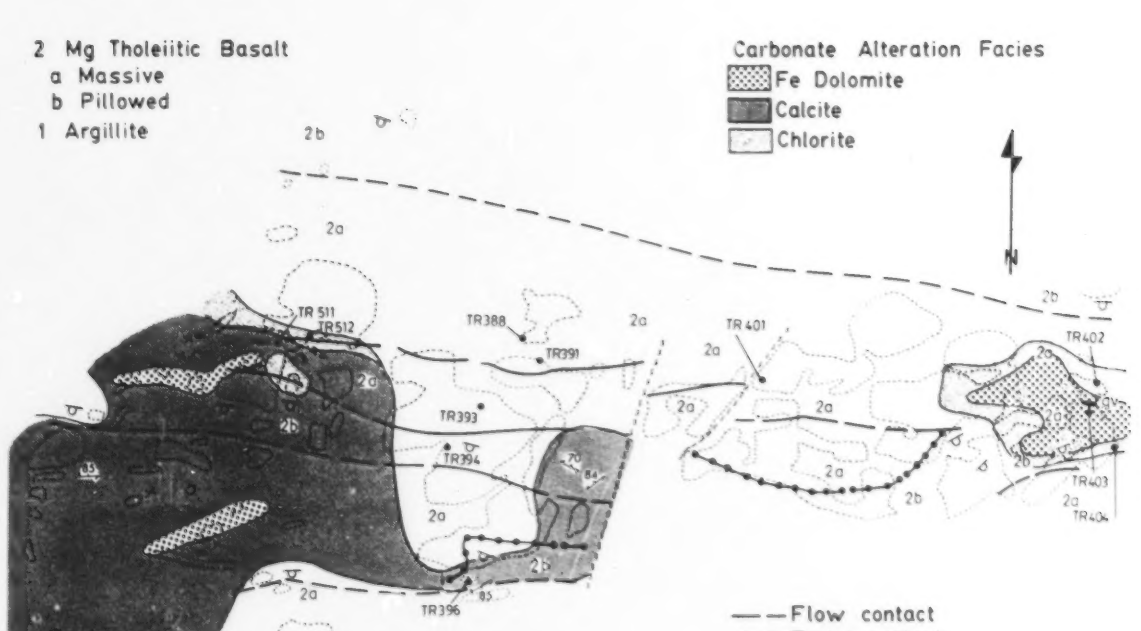

Figure 9–Geological plan of the Dobell property, Tisdale Township study-area illustrating the distribution of carbonate alteration facies. The calcite-rich alteration facies predominates in the largest discordant alteration zone (Geology from Fyon 1980a).

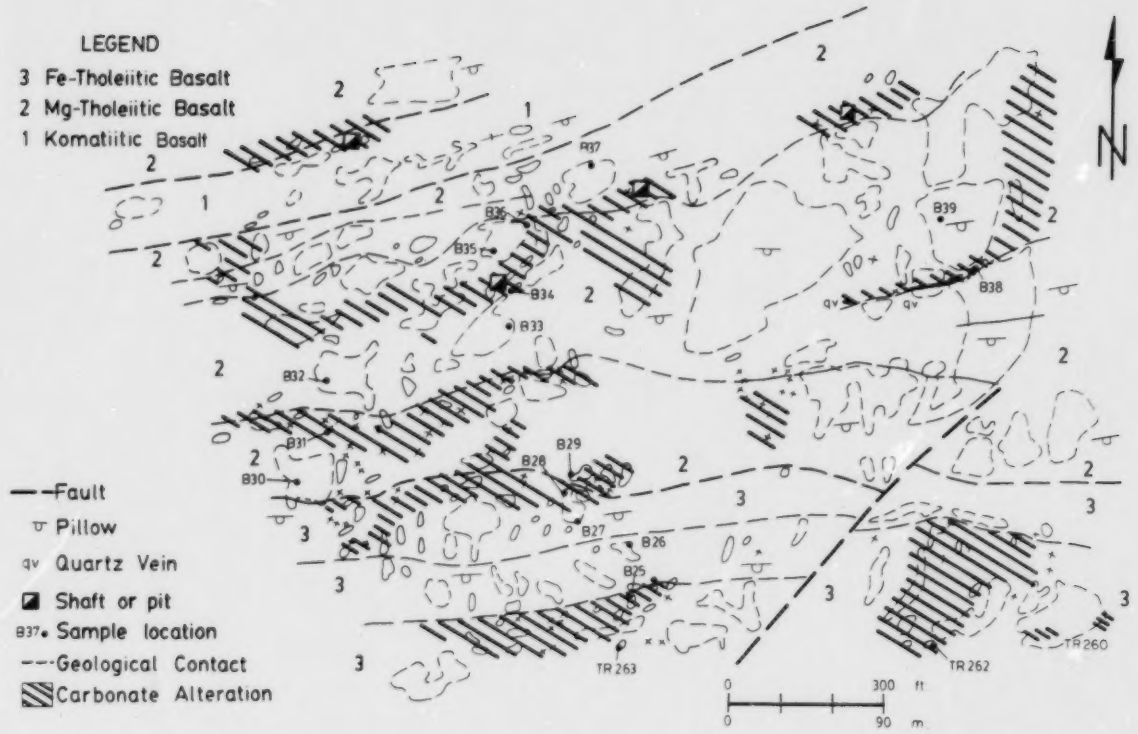

Figure 10–Geological plan of the Kinch property, Tisdale Township study-area illustrating the distribution and morphology of stratabound and discordant carbonate alteration zones. Although unsubdivided, the dolomite alteration facies predominates (geology after Fyon 1980a).

ness of the transitional zone is less than 0.5 m. A quartz vein also occurs in the dolomite zone; this vein has yielded no mineable gold.

In stratabound alteration zones, the alteration assemblage contacts trend parallel to, or occur along flow contacts. On the Kinch property (Figure 10), where some alteration zones are clearly localized along flow contacts, the top and base of the adjacent flows are carbonatized, and the alteration intensity decreases away from the flow-top breccia zone. Thus, both flows were in place prior to the alteration event. The hydrothermal solution flux was maximum along the permeable flow-top breccia zone. On the east edge of the Kinch property, a discordant alteration zone cuts up through the massive and pillowed facies of a flow, but extends out laterally along the first flow contact. This, again illustrates the importance of permeable flow top breccia zones as a control on the distribution of stratabound alteration zones.

Numerous quartz veins occur within the dolomitic alteration zones, all of which have been test pitted or trenched. No gold production, however, has been reported from this area.

The morphologies and constitutions of the carbonate alteration zones exposed both on surface and underground at the Aunor, Delnite, and Buffalo Ankerite Mines in the Deloro Township study-area (Map 2), are similar to those observed in the Tisdale Township study-area. However, there is one significant difference. The ore zones of these mines occur at the top of the lower volcanic sequence within a unit of carbonatized, Mg-tholeiitic basalt which is overlain and underlain by carbonatized ultramafic komatiitic flows (Map 2). As illustrated on the Buffalo Ankerite property (Figure 11, Chart B, back pocket), the mineralized zone, outlined by the two open pits, lies within carbonatized, Mg-tholeiitic basalts which are overlain and underlain by carbonatized, ultramafic komatiitic flows. The ore-bearing carbonatized sequence is overlain by carbonate-free, ultramafic komatiitic flows which constitute the base of the upper lithological sequence. That is, the distribution of carbonatized rock is dramatically controlled by a major lithological contact between two ultramafic, komatiitic flow units. This relationship is also observed on surface at the Delnite Mine (Pamour #3), where pervasively carbonatized, ultramafic komatiitic flows are overlain by carbonate free, Mg-tholeiitic basalts (Figure 12).

Alteration Timing

From the field relationships of the carbonate alteration zones and certain petrographic characteristics of the altered rock, it is deduced that the pervasive carbonatization event post-dated the earliest sea floor metamorphism, but predated the regional, low grade metamorphism and related deformation of the Tisdale Group. The term sea floor metamorphism denotes alteration of the volcanic rocks occurred at low temperatures (<200°C) and pressures (0.5 kb) and included all processes coincident with the filling of inter and intra-particle porosity (Dimroth and Lichtblau 1979).

Vesicles are filled by quartz (after chalcedony; Photo 2), quartz-chlorite (after chalcedony and possibly zeolites or clays; Photo 3) and quartz-calcite (Photo 4). The presence of calcite as a vesicle-filling mineral indicates that car-

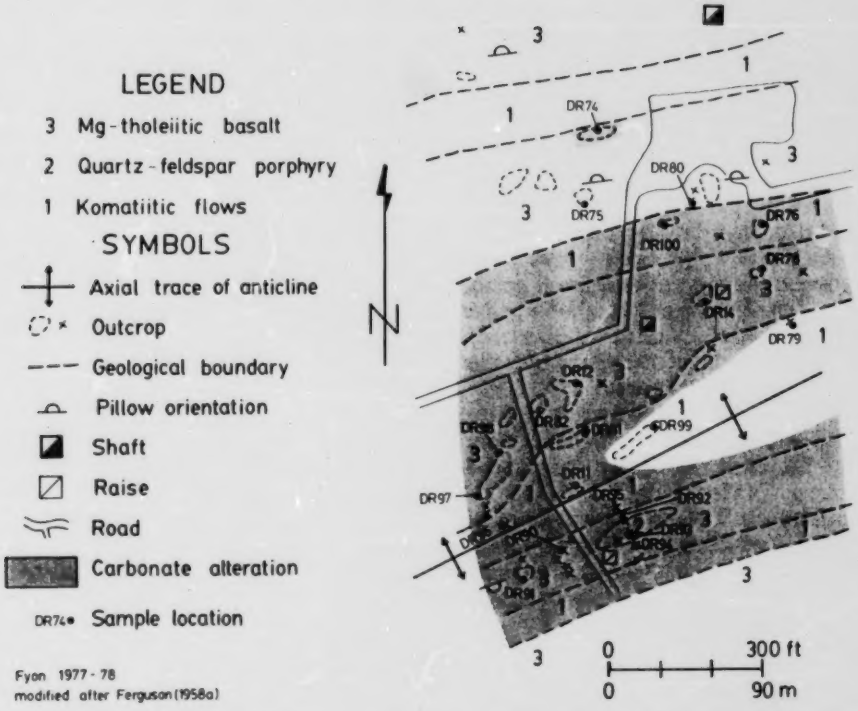

Figure 12–Geological plan of the Delnite Mine (Pamour #3), Deloro Township study-area. Note control on the vertical distribution of carbonate alteration by a lithological contact between an ultramafic komatiitic flow unit and the overlying Mg-tholeiitic basalts.

bonate introduction was coincident with the vesicle-filling event. Most of the carbonate introduction is, however, volumetrically related to the pervasive carbonatization event, during which carbonate (calcite and ferroan dolomite) replaced both the rock matrix- and the vesicle-filling minerals (Photo 3).

A pre-regional, low grade metamorphic and deformation age of the pervasive carbonatization is deduced from the presence of equivalent tectonic fabrics (lineations and foliations) in both the freshest and most carbonatized rocks of a given area. For example, both the carbonatized and least altered flows exposed on the Davidson-Tisdale property (see Figure 8) bear the same northerly trending lineations. This indicates that the carbonate alteration predated the first period of regional, north-south deformation of the Tisdale Group.

The restriction of the carbonate alteration to the immediate ore-bearing unit at the Aunor, Buffalo Ankerite, and Delnite Mines suggests that this carbonate alteration event predated the emplacement of the overlying carbonate-

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Photo 2–Vesicle filled by partly recrystallized calcite (dark) and quartz. Relict colloform textures suggest the quartz is after chalcedony.

poor komatiitic and Mg-tholeiitic flows. That is, this alteration was synvolcanic and took place during longer periods of volcanic hiatus during which hydrothermal fluids discharged directly onto the sea floor.

Some of the larger metamorphic quartz veins are also associated with carbonatized wall rock. Consequently, there appears to be a time continuum over which the rocks were altered. This continuum began with the fixation of carbonate during the initial sea water or diagenetic alteration of the flows, was followed by the pervasive carbonate alteration which pre-dated the major tectonic events, and terminated during the regional metamorphism of the volcanic pile.

Thus, in the detailed study-areas, the pervasive carbonate alteration was an integral part of the early sea floor and subsea floor hydrothermal history of the volcanic pile.

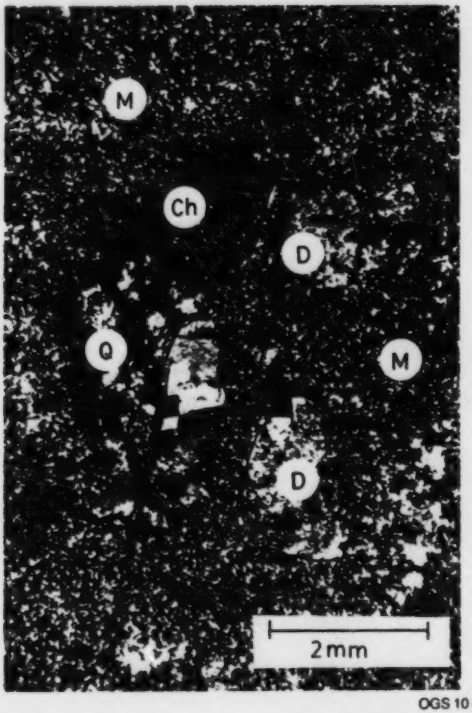

Photo 3–Vesicle filled by chlorite (Ch) and remnants of quartz (Q). Dolomite (D) replaces both rock matrix (M) and the vesicle filling minerals. This dolomite introduction took place during the pervasive carbonatization event.

CARBONATIZATION ENVIRONMENT

Subsea Floor Environment

All discordant and stratabound carbonate alteration zones exposed in the Tisdale Township study-area, as well as some in the Deloro Township study-area (Skynner Lake; Fyon and Karvinen 1978) developed within the volcanic pile by passage of hydrothermal fluids up through joint or fracture systems to form discordant alteration zones and along flow contacts or flat joint systems to form stratabound alteration zones (Figure 13). The vertical extent of the discor-

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Photo 4–Vesicle filled by blocky quartz rim and calcite at the core.

dant carbonate alteration is not restricted to a particular flow or flow unit, but rather it dies out gradually in the vertical dimension.

Although not represented in the detailed study-areas, carbonate alteration envelopes have been observed about synvolcanic felsic and ultramafic feeder dikes cutting Deloro Group lithologies (Fyon *et al.* 1980). This association suggests that this carbonate alteration formed in small scale hydrothermal systems derived from pore fluids circulated convectively by the heat supplied from the dikes. The salient characteristics of this subsea floor, alteration environment included the absence of clastic sediments, auriferous exhalites, and large, stratabound, felsic volcanic complexes (QFP bodies[1]). The presence of only one

[1]QFP is an abbreviation meaning 'Quartz Feldspar Porphyry', and is used throughout the text.

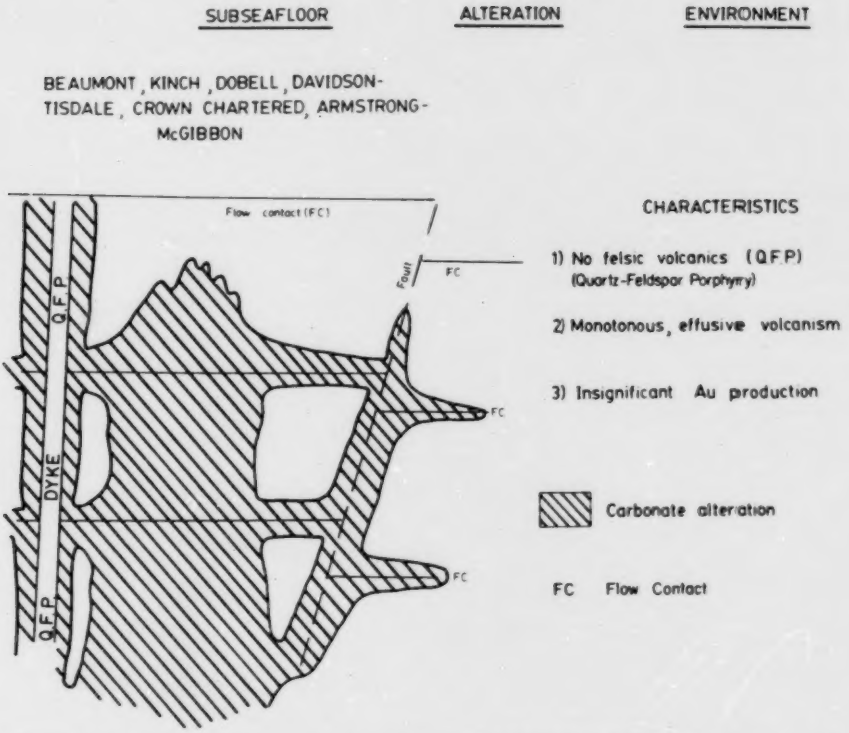

Figure 13–Sketch illustrating the essential characteristics of the subsea floor carbonate alteration environment. Little gold has been won from carbonate alteration zones which formed in this environment.

interflow, clastic argillite, which trends easterly across the north-central part of the Tisdale Township study-area (*see* Figure 3: and Map 1, back pocket), indicates there were few lengthy breaks during the effusive submarine volcanism during which clastic or chemical sediments could have accumulated. The hydrothermal solution conduits which developed in this subvolcanic environment were completely enclosed by volcanic rock. The hydrothermal solutions did not debouch directly onto the sea floor.

Sea Floor Environment

The second distinct environment in which rocks have been altered is interpreted from the morphology of the carbonate alteration zones present at the Aunor, Delnite, and Buffalo Ankerite Mines. This alteration took place at or just below the paleosea floor/sea water interface (Figure 14). This environment

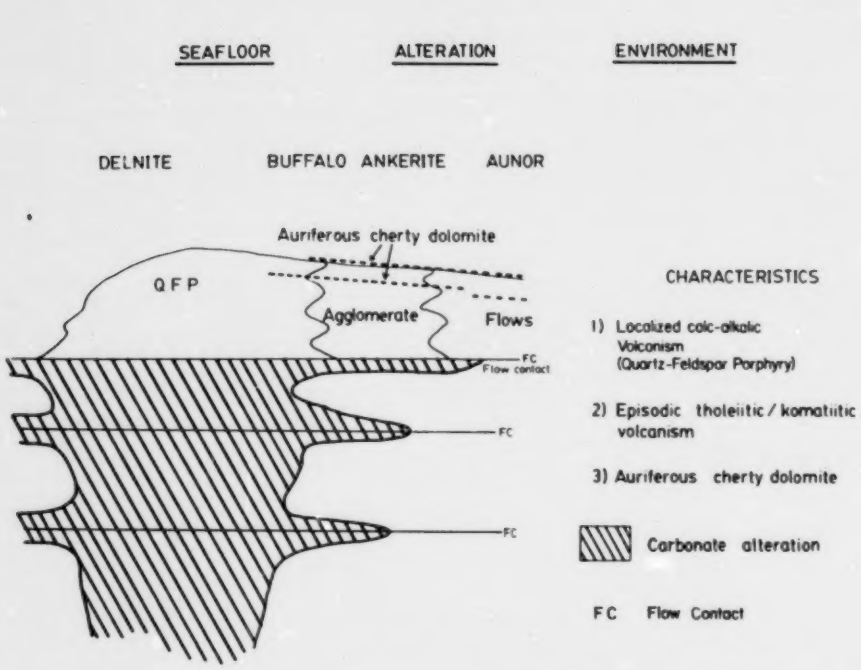

Figure 14–Sketch illustrating the essential characteristics of the auriferous, sea floor alteration environment.

is characterized by the presence of stratiform, auriferous, exhalative sediments, explosive volcanic products (agglomerates), and localized felsic volcanic complexes (QFP bodies). The carbonate alteration, whether discordant or stratabound, is restricted to a particular stratigraphic unit which may consist of diverse lithologies. This altered unit is overlain by carbonate-free lithologies. Interbedded within the carbonatized volcanic flows are the auriferous, dolomitic exhalites.

The restriction of the auriferous exhalites to this alteration environment implies that the hydrothermal fluids discharged directly onto the sea floor. During the precipitation of the exhalites, supply of clastic and volcanic material to the area must have been temporarily arrested, for such material would have diluted the chemical precipitate. Hence, this alteration environment was characterized by episodic volcanism during which more lengthy volcanic hiatuses permitted discharge of the hydrothermal fluids onto the sea floor, resulting in the precipitation of the auriferous exhalites.

Given that the Tisdale and Deloro Township study-areas are stratigraphically equivalent, it is apparent that the styles of volcanism represented in both study-areas differ. In the Tisdale Township study-area, the style was one of continuous and effusive tholeiitic and komatiitic submarine volcanism. Con-

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Photo 5–Agglomerate exposed in the east pit on the Buffalo Ankerite property (*see* Figure 11). Fragments consist of quartz-feldspar porphyry (white) and carbonatized ultramafic komatiite (grey colours). The matrix contains abundant disseminated pyrite.

versely, in the Deloro Township study-area, the presence of chemical sediments suggests that the mafic and ultramafic volcanism was episodic. Time equivalent with the chemical sediments are localized centres of felsic volcanism (quartz-feldspar porphyries) which consist in part of explosive products (agglomerate on Buffalo Ankerite property; (*see* Figure 11, Photo 5).

In addition to the stratiform gold deposits of the Pamour #3 (Aunor and Delnite) and Buffalo Ankerite Mines, some of the mineralization at the Dome (Fryer and Hutchinson 1976; Roberts 1980; Fryer *et al.* 1979), Paymaster Porcupine (Longley and Lazier 1948; Map 2075, Ferguson *et al.* 1968), Hollinger, and McIntyre Mines (Karvinen 1981) is syngenetic, and formed on the sea floor in proximity to bodies of quartz-feldspar porphyry. Although these deposits lie higher in the Tisdale Group, associated with iron-rich tholeiitic basalts, it is again the nature of the volcanic environment, dominated by localized felsic volcanic centres and episodic volcanism which dictates the style of rock alteration and the likelihood of syngenetic gold deposition.

SIGNIFICANCE OF THE QUARTZ-FELDSPAR PORPHYRY COMPLEXES

The presence of the stratabound porphyry bodies is an important characteristic of the metalliferous, sea floor alteration environment. These porphyries, which are restricted to Formations IV and V of the Tisdale Group, have been envisioned as having been a source of gold in the Porcupine Camp (Carter 1948; Ferguson *et al.* 1968; Griffis 1962; Karvinen 1978a).

With respect to the porphyries, there is a spatial and chemical zoning of the auriferous exhalites. Carbonate alteration appears to be most intense beneath and laterally adjacent to the porphyries. Geological plans of the Paymaster, Porcupine (Longley and Lazier 1948), Buffalo Ankerite (Kinkel 1948), Aunor (Buffam 1948), and Delnite Mines (Taylor 1948) reveal that the frequency of exhalites decreases with increasing lateral distance from the perimeter of a porphyry body. Furthermore, C.S. Longley and T.A. Lazier (1948) observed that with increasing distance from the Paymaster porphyry, the relative abundance of chert in the exhalites decreased, carbonate increased, and the gold tenor dropped. There is also a suggestion that carbonate alteration is most intense in the footwall beneath the porphyries and immediately adjacent to the porphyries. With increasing lateral distance away from the porphyries, the intensity of carbonate alteration decreases.

These tentative observations suggest that the locus of hydrothermal discharge into the hydrosphere was centred about the porphyry complexes. Given the probability that the porphyry complexes represent small felsic volcanic centres (Dunbar 1948; Davies 1977; Karvinen 1976, 1978a; Davies and Luhta 1978; Pyke 1981, 1982; Fyon 1980a) and related hypabyssal intrusives (Griffis 1962; Graton and McKinstry 1933), this hydrothermal focusing might reflect convective circulation of hydrothermal fluids driven by the heat of crystallization released from the felsic volcanic rocks and related feeder dikes. Alternatively, the synvolcanic structural regime which controlled the localization of the felsic volcanic complex also served as an efficient hydrothermal fluid conduit system.

The environment which characterizes the sea floor alteration environment and hosts the porphyries, is also characterized by episodic volcanism during which the auriferous exhalites accumulated. Typically, during the evolution of an Archean, submarine volcanic terrain, the waning stages of a felsic volcanic episode are inherently associated with periods of quiescence during which clastic or chemical sedimentation takes place (Goodwin *et al.* 1972).

Implications that the auriferous exhalites formed in an environment not unlike that in which stratabound, base-metal massive sulphide deposits occur are provided by:

1) The presence of areally restricted, stratabound quartz-feldspar porphyry complexes thought to represent intrusive/extrusive felsic volcanic centres,

2) The spatial association between the porphyry complexes and the auriferous exhalites,

3) The observed chemical and textural zonation of the auriferous exhal-

ites of increasing distance laterally away from the perimeter of a porphyry complex,

4) The tentative distribution of carbonate alteration intensity in the mineralized environment.

The significant differences between these two deposit types include:

1) Metal association;

2) Lateral continuity of auriferous exhalites, 1 to 2 km from the porphyries;

3) Mineralogy of ores;

4) Type of rock alteration.

Hence, the porphyries are not envisioned as a source of gold. Rather, these rocks represent a favourable geological environment in which hydrothermal fluid fluxed through the volcanic pile, debouched onto the sea floor, and resulted in the accumulation of auriferous exhalites.

ORIGIN OF HYDROTHERMAL FLUIDS

Studies of Phanerozoic, submarine volcanic suites reveal that the post-eruptive, thermal and lithogeochemical history of the volcanic pile is strongly influenced by chemical exchange with sea water which gains access to the volcanic pile by burial of water-saturated surface flows (Andrews, A.J.,1977) and by downward circulation in large-scale, subsea floor convective systems (Hart 1969; Garlick and Dymond 1970; Muehlenbachs and Clayton 1972; Spooner and Fyfe 1973; Aumento *et al.* 1976; Muehlenbachs 1977; Scarfe and Smith 1977). Compelling textural evidence has been presented which indicates that Early Precambrian (Archean) and Phanerozoic submarine volcanic rock underwent similar sea floor metamorphic histories (Dimroth and Lichtblau 1979; Baragar *et al.* 1979).

The products of lower temperature (<200°C), sea water alteration of basaltic glass include; palagonite, clay minerals, zeolites, carbonates, chalcedony, albite, and iron oxides (Baragar *et al.* 1977; Andrews, A.J.,1977; Scarfe and Smith 1977). The phyllosilicates are enriched in potassium, boron, lithium, and oxygen-18 with respect to either sea water or the igneous precursor phases (Thompson and Melson 1970; Humphris and Thompson 1978; Garlick and Dymond 1970). In general, greater degrees of rock/sea water interaction produce more secondary alteration products, which in turn, enriches the whole rock in boron, lithium, potassium, and oxygen-18.

Vesicle-filling mineral sequences observed in the least altered flows from the Timmins area (*see* Photos 2,3,4) are interpreted to be similar to those described by E. Dimroth and A.P. Lichtblau (1979), and are considered to be indicative of sea water alteration. In the Timmins area, the former presence of the diagnostic, low temperature vesicle-filling clay and zeolite phases, however, can only be inferred because these phases, if initially present, were subsequently replaced by chlorite and clinozoisite during the regional, low grade metamorphism.

Some selected geochemical characteristics of unaltered and sea water altered, modern, submarine basalts are compared in Table 1. Modern submarine

TABLE 1 | COMPARISON OF BORN (B), LITHIUM (Li), POTASSIUM (K_2O), WATER (H_2O) AND OXYGEN-18 COMPOSITIONS OF MODERN SEA WATER ALTERED SUBMARINE BASALTS WITH THOSE IN BASALTS FROM THE TIMMINS AREA.

	MODERN SUBMARINE BASALTS		TIMMINS DATA ALTERED BASALTS		
Element	Unaltered	Sea Water Altered	Ore Associated	No Ore Association	Least Altered
B ppm	2–9 X=5 y=1.6 n=8 (1,2)	5–130 X=13.2 y=14.1 n=46 (1,2)	5–1000 X=528 y=678 n=20	5–40 X=23 y=48 n=98	5–7 X=5.4 y=0.9 n=5
Li ppm	3–8 X=5 y=2 n=8 (1,2)	3–60 X=20.8 y=31 n=46 (1,2)	3–58 X=39 y=13.7 n=21	5–80 X=19.3 y=10.9 n=142	1–35 X=12.8 y=7.9 n=12
K_2O[a] wt. %	X=0.20 n=12 (3)	X=0.80 n=12 (3)	0.1-3.34 X=1.24 y=1.01 n=20	0.02-3.48 X=0.67 y=0.85 n=130	0.01-1.30 X=0.14 y=0.14 n=15
H_2O wt.%	<0.5	0.4–7.0 X=3.13 y=1.82 n=45 (1,4)	>3.3	>3.3	2.3–4.1 X=3.49 y=0.47 n=17
yO^{18} whole rock	5.5–6.5 X=5.9 y=0.3 n=40 (6,7)	5.5–18 X=9.04 y=2.62 n=28 (6,7)	11.15–14.29 X=11.94 y=1.43 n=8 (5)	8.26–9.74 X=8.98 y=0.74 n=3 (5)	

a: anhydrous value
1: Humphris and Thompson (1978)
2: Thompson and Melson (1970)
3: Aumento *et al.* (1976)
4: Hart and Nalwalk (1970)
5: Kerrich and Fryer (1979)
6: Muehlenbachs and Clayton (1972)
7: Muehlenbachs (1977)

X: mean
y: standard deviation
n: number of samples

basalts which have reacted at lower temperatures (<200°C) with sea water are enriched in boron, lithium, potassium, water, and the oxygen-18 whole rock composition with respect to their least altered, submarine equivalents. All altered basalts from the Timmins area, regardless of proximity to gold mineralization, are also enriched in these constituents with respect to modern, unaltered submarine basalts. In addition, those altered basalts which host gold mineralization show even greater enrichments with respect to those carbonatized basalts which are not associated with gold mineralization.

Hence, the carbonatized tholeiitic basalts from the Timmins area appear to have the distinctive trace element geochemical signature of lower temperature (<200°C), sea water alteration. This suggests that sea water was a major component of the hydrothermal fluid (Fyon 1980a).

The enrichment in boron, lithium, and potassium, is greater in the productive alteration zones than the concentration in the barren alteration zones. This suggests that greater volumes of sea water hydrothermal fluids were fluxed through those metalliferous alteration zones, than through the barren alteration zones. High fluid flux would be favoured by a permeable "plumbing" network and by lengthy volcanic hiatuses required to permit both recharge and discharge of the hydrothermal system. Precipitation from the discharged hydrothermal fluids produced the auriferous, cherty dolomite exhalites.

Hart *et al.* (1970) and Hart and Brooks (1977) have argued that the Archean upper mantle was probably less depleted in many trace elements, particularly in large ion lithophile elements, than the present upper mantle. Therefore, conclusions drawn from comparing the geochemistry of Archean and modern oceanic ridge basalts could be suspect. K.C. Condie (1976) suggested that, if anything, the Archean upper mantle was geochemically heterogeneous, particularly in alkali and related elements.

To test the validity of the above geochemical comparisons, certain geochemical characteristics of 17 of the least-altered Mg-tholeiitic basalts, collected from Formation IV of the Tisdale Group, were compared with those geochemical characteristics of the fresh modern submarine basalts (Table 1).The least-altered Timmins basalts contain less than 4.1 weight percent loss on ignition, whereas their equivalent highly altered basalts have a total volatile range from 4 to 19 weight percent. Listed in Table 1 are the boron, lithium, potassium, and total volatile contents of these least-altered basalts from the Tisdale Group.

Compared to the freshest, modern submarine basalts (Table 1), the least-altered basalts from the Timmins area are slightly enriched in lithium and total volatiles, but have comparable boron and potassium contents. This compositional similarity between the freshest Archean and modern submarine basalt suites at least with respect to boron, lithium, and potassium abundances, suggests that the comparison is valid and the conclusions based on that comparison are sound.

R. Kerrich and B.J. Fryer (1979) recognized the significance of the heavy oxygen-18 whole rock compositions of altered basalts from the Timmins area. Some quartz vein material, however, cuts syngenetic gold ore. These authors, based on the oxygen isotope composition of the quartz vein material, inferred that carbonate alteration and the formation of the auriferous quartz veins was a consequence of rock/metamorphic hydrothermal fluid interaction.

From the writers' detailed field studies, it is apparent that the carbonate alteration predated the regional metamorphism and deformation of the volcanic pile, and locally was synvolcanic. The petrographic and geochemical characteristics of the carbonatized rock suggest their alteration by sea water hydrothermal fluids. We propose therefore, that the carbonate alteration and precipitation of auriferous cherty-dolomite exhalites are consequences of Archean rock/sea water interaction. Metamorphic fluids served only to locally redistribute original, syngenetic, gold mineralization.

SIGNIFICANCE OF ULTRAMAFIC FLOWS

Recent genetic models of gold metallogenesis favour a source bed concept (Viljoen *et al.* 1970; Pyke 1975b, 1981, 1982), suggesting that komatiitic flows are significantly enriched in gold with respect to other rock types. At the 5 percent significance level, there is no statistical difference between the mean gold abundances of ultramafic komatiitic and Mg-tholeiitic flows from the Timmins area (Figure 15). Note that all samples have been altered to various degrees, but none are spatially associated with economic gold mineralization. Gold characteristics of other mafic and ultramafic rocks from the Kirkland Lake area (Andrews, D.J.,1977; Tihor and Crocket 1977), Munro Township area (MacRae and Crocket 1977), Kakagi Lake area (Kwong and Crocket 1978), and the Red Lake area (Cowan and Crocket 1980), reveal that background gold abundances in these metavolcanics range from one to five parts per billion. Hence, the appeal to ultramafic flows in general to be anomalous sources of gold is not supported by the available analytical data.

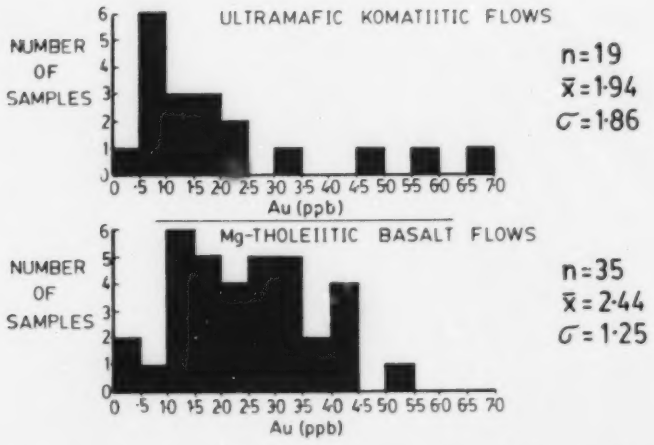


Figure 15–Comparison of gold abundances in freshest and altered ultramafic komatiitic flows and Mg-tholeiitic basalts. Statistically, the gold abundances are indistinguishable.

How then, might the observed spatial association between some Archean gold deposits and ultramafic flows be rationalized? The unstable nature of these ultramafic rocks in the presence of CO_2-charged aqueous fluids has been demonstrated experimentally (Greenwood 1967; Johannes 1969) and on the basis of field data (Pyke 1975b, 1981, 1982). The relative ease with which ultramafic flows are carbonatized facilitates the removal of gold during rock alteration, particularly for those ultramafic rocks bearing immiscible sulphide droplets (Keays 1979; Keays *et al.* 1979; *see* also Groves and Keays 1979). Thus, the observed spatial association between some types of Archean gold mineralization and ultramafic flows might reflect the ease with which these rocks are carbonatized and indigenous gold mobilized. This gold depletion is not observed in the ultramafic flows from the Timmins area (Figure 15).

Alternatively, the spatial association of some types of Archean gold deposits and ultramafic flows might reflect the geological environment in which these komatiitic flows and the gold mineralization evolve. In this part of the Abitibi Belt, extrusion of ultramafic, komatiitic flows marks the onset of a new volcanic episode (Pyke 1975b, 1981, 1982; Jensen 1978). These ultramafic flows are interbedded with felsic volcanic products from the waning, older volcanic episode (*compare with* Formation III, Deloro Group). At this stage, periods of volcanic quiescence are more abundant and rock/sea water hydrothermal interaction is favoured. Chemical-mass transfer from the rock to the hydrosphere promotes the accumulation of chemical sediments which are deposited on both the felsic and ultramafic rocks. Hence, in this environment, gold exhalites would be expected to be spatially associated with ultramafic flows.

SIGNIFICANCE OF THE DESTOR-PORCUPINE FAULT

The role of volcanic hiatuses during which sea water hydrothermal fluids are discharged from the rock column onto the sea floor is of fundamental importance for the generation of the auriferous chemical sediments. However, to establish and maintain a sea water hydrothermal system, a suitable "plumbing" system must prevail to facilitate large scale penetration of sea water into the oceanic crust. In modern day oceanic environments, sea water penetration into the oceanic lithosphere is active along the ocean ridge systems (Andrews and Fyfe 1976; Andrews, A.J. 1977; Baragar *et al.* 1977; Garlick and Dymond 1970; Hart 1969; Muehlenbachs and Clayton 1972; Muehlenbachs 1977; Spooner and Fyfe 1973).

In the Abitibi Belt, it has long been recognized that the gold deposits are spatially associated with regional tectonic lineaments (Figure 16) such as the Destor-Porcupine Fault, the Larder Lake Break, and the Kirkland Lake Break (Burrows 1924; Hurst 1936; Thompson 1943; Dunbar 1948; Ferguson *et al.* 1968). The Destor-Porcupine Fault system localized some felsic (quartz-feldspar porphyry complexes) and ultramafic volcanism as well as clastic sedimentation (Pyke 1981, 1982). This regional structure has been interpreted as a part of a major fracture system in the Archean crust, and was probably related to rifting (Pyke *et al.* 1978; Pyke 1981, 1982).

The fault system also probably served as a locus of sea water-penetration

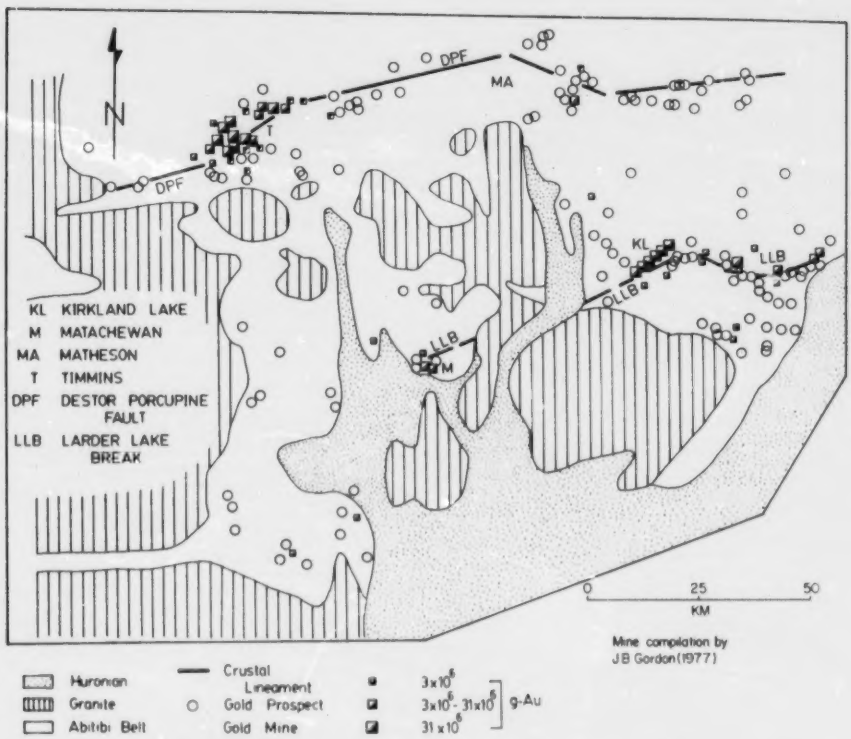


Figure 16- Regional spatial association between major fault zones and gold mines and prospects in the northeastern part of the Abitibi Greenstone Belt in Ontario (from Gordon 1977).

and circulation through the oceanic crust (Fyon 1980a).

Thus, the observed regional spatial association between gold deposits and major, structural lineaments in this part of the Abitibi Greenstone Belt (Figure 16) reflects an important symbiotic relationship between the volcano-tectonic environment, hydrothermal activity, and ore genesis.

GOLD EXPLORATION CRITERIA

Exploration for gold in the northeastern part of the Abitibi Greenstone Belt must use a multi-disciplinary approach that integrates geological, geochemical, and geophysical techniques. Some geological and lithogeochemical criteria with which favourable target areas can be identified are outlined in the next section.

Regional Geological Considerations

The gold metallogeny of the Timmins, Larder, and Kirkland Lake areas is intimately related to the geotectonic evolution of the Abitibi supracrustal sequence (Pyke 1981, 1982). Virtually all past and present gold mines are located in proximity to major east-west trending fault zones (Figure 16). Examples of such faults are the Destor-Porcupine, Kirkland Lake or Larder Lake Faults, within which sedimentation and komatiitic volcanism appear to have been localized (Pyke 1978, 1981, 1982). Furthermore, carbonatized volcanic rock and small stocks of QFP or syenite are commonly found within or near the major fault zones (Pyke 1981, 1982).

Even though the distribution of gold deposits and prospects is not uniform along the Destor-Porcupine or Larder Lake 'breaks' (Figure 16), these regional fault zones still represent regions of the highest gold potential within this part of the Abitibi Greenstone Belt (Hurst 1936; Burrows 1924; Pyke 1981, 1982).

Local Geological Considerations

Within and near the Destor-Porcupine Fault zone, the morphologies of carbonate alteration zones can be defined by detail mapping. Hence, those alteration zones which appear to have formed at or near the sea floor/sea water interface can be distinguished from those which formed deeper in the volcanic pile. The presence of felsic volcanic rocks, and quartz-feldspar porphyry bodies, particularly when situated in or near a sea floor alteration zone, defines one of the most favourable target areas (*see* Figure 14).

Lithogeochemical Guides

A comprehensive summary of a large number of elements which are commonly associated with gold deposits has been given by Boyle (1979). To establish which of the pathfinder elements occur with gold mineralization in the Porcupine Camp, an orientation lithogeochemical survey was carried out. For the present study, a number of trace elements including Ag, Au, As, B, Ba, Be, Bi, Co, Cr, Cu, Ga, Li, Mo, Ni, Pb, Rb, Sb, Sc, Sn, Sr, V, W, Y, Zn, and Zr and major elements SiO_2, Al_2O_3, Fe_2O_3 total, MgO, CaO, Na_2O, K_2O, TiO_2, MnO, P_2O_5, CO_2, S, LOI were determined on selected samples by the Geoscience Laboratories, Ontario Geological Survey, and by the senior author at McMaster University. A sample suite (Appendices 1,2 *see microfiche, back pocket*) from the regional data file (Fyon 1980b) was selected to ensure representation of all alteration facies in both metalliferous and barren carbonate alteration zones. For prospective pathfinder elements, appropriate thresholds were determined and the scale of the primary dispersion halo about the gold mineralization was established.

Samples have been classified into 'productive' and 'unproductive' groups. 'Productive' samples were collected from altered rock located within the ore

zones of the Pamour #3 (Aunor and Delnite) and Buffalo Ankerite Mines; whereas 'unproductive' samples were collected from the numerous barren alteration zones present in the Tisdale Township study-area. In addition, some unproductive samples were collected from barren carbonate alteration zones which lie stratigraphically above the ore zones in the Deloro Township study-area. Discrimination between barren and metalliferous alteration zones was achieved by comparison of the trace element abundances of the productive and unproductive sample populations. Whole rock samples, rather than mineral separates, were used to minimize sample processing and hence to minimize the possibility of sample contamination.

ANALYTICAL METHODS

Major element analyses were carried out at McMaster University. Fusion pellets, prepared using the method of Norrish and Hutton (1969), were analysed on a Philips automatic sequential spectrometer Model PW 1450. For SiO_2, Al_2O_3, Fe_2O_3 total, MgO, CaO, K_2O, TiO_2, MnO, P_2O_5, precision and accuracy are better than 10 percent. Sodium was determined by XRF using a powder pellet yielding a comparable precision and accuracy.

The trace elements sought, the analytical laboratory, analytical precision, and detection limits are listed in Table 2.

DATA TREATMENT

The geochemical data for productive and unproductive groups have been plotted on binary diagrams as a function of alteration intensity, expressed as CO_2 weight percent, because the abundances of certain elements vary greatly as a function of rock type and alteration intensity (Fyon 1980a). On these diagrams, the Mg-tholeiitic basalts have been treated separately from the komatiitic volcanic rocks. This distinction is particularly important since pervasively carbonatized ultramafic flows may be enriched in CO_2 by as much as a factor of two with respect to pervasively carbonatized basaltic flows.

THRESHOLD DETERMINATION

The threshold determination is an important aspect of the data treatment. In the most simple case, two sample populations are to be distinguished on the basis of one chemical component; for example, gold abundance. A threshold can be calculated by optimizing a linear function such that the threshold defines the maximum difference between the two previously defined groups of populations using that chemical component. A modification of the discriminant function described by J.C. Davis (1973) was used for this univariate problem.

Threshold levels established here are higher than those reported by J.F. Davies *et al.* (1980) and R.E.S. Whitehead *et al.* (1980). This is attributed to the

TABLE 2 DESCRIPTION OF THE ANALYTICAL PARAMETERS FOR THE TRACE ELEMENTS INVESTIGATED.

Trace Element	Analytical Laboratory	Analytical Method	Detection Limit	Precision
Ag	OGL	S	1 ppm	± 10
Au	MU	RNAA	0.1 ppb	± 15 (5 ppb)
		EINAA	2 ppb	± 20 (5–100 ppb)
				± 50 (5 ppb)
As	OGL	AA	1 ppm	± 10
B	OGL	S	5 ppm	± 10
Ba	OGL	AA	5 ppm	± 10
Be	OGL	AA	1 ppm	± 10
Bi	OGL	AA	0.1 ppm	± 10
Co	OGL	AA	5 ppm	± 10
Cr	OGL	AA	5 ppm	± 10
Cu	OGL	AA	5 ppm	± 10
Ga	OGL	S	1 ppm	± 10
Li	OGL	AA	5 ppm	± 10
Mo	OGL	S	1 ppm	± 10
Ni	OGL	AA	5 ppm	± 10
Pb	OGL	AA	10 ppm	± 10
Rb	MU	XRF	5 ppm	± 15
Sb	OGL	AA	0.1 ppm	± 10
Sn	OGL	S	3 ppm	–––
Sr	OGL	S	1 ppm	± 10
V	OGL	S	10 ppm	± 10
Y	OGL	S	10 ppm	± 10
Zn	OGL	AA	5 ppm	± 10
Zr	OGL	S	10 ppm	± 10
W	OGL	S	500 ppm	–––
S	OGL	Leco	0.01 wt %	± 10
CO_2	OGL	Leco	0.01 wt %	± 10
L.O.I.	MU	C	0.01 wt %	± 5

AA: Atomic absorbtion.
C: Conventional; ignition at 1000°C for 30 minutes.
EINAA: Epithermal, instrumental, neutron activation analysis.
RNAA: Radiochemical, neutron, activation analysis.
S: Optical emission.
XRF: X-ray fluorescence.
OGL: Ontario Geoscience Laboratory.
MU: McMaster University.
Leco: Leco carbon determination.
–––: All data for this study below detection limit.

relatively restricted area (parts of Whitney, Tisdale, Deloro, and Ogden Townships) sampled for the present study, and to the different scales of target area to which the dispersion haloes are applicable. Our thresholds (Fyon and Crocket 1979) were optimized to outline thin (<100 m) ore-bearing zones within a region which was subjected to widespread hydration and carbonatization. That is, our thresholds were selected to outline anomalies on a deposit scale, suitable as diamond-drill targets. The thresholds reported by Davies *et al.* (1980) and Whitehead *et al.* (1980) serve to outline large scale (township scale) areas of rock alteration in which several occurrences of gold mineralization are likely.

TRACE ELEMENT SCREENS

Of the trace elements studied, only seven (As, Au, B, Cu, Li, Pb, Sb) discriminate between metalliferous and barren carbonate alteration zones. Of the other trace elements, some are enriched in carbonatized rock regardless of proximity to gold mineralization (for example S, CO_2), while others are unaffected by carbonate alteration intensity (for example Zn, Ag).

Arsenic

Background abundances of arsenic generally do not exceed 100 ppm (Figure 17), and a threshold of approximately 70 ppm permits discrimination between productive and unproductive Mg-tholeiitic basalts.

Although more overlap occurs between productive and unproductive komatiites, a threshold of 70 ppm permits correct classification of 75 percent of these samples.

Gold

Background gold abundances in unproductive mafic and ultramafic flows rarely exceeds 5 ppb (*see* Figures 15,17) regardless of the degree of carbonate alteration. Clearly, the carbonate alteration zones do not *a priori* represent zones having anomalous gold abundances. This fact compliments the empirical observation that not all zones of carbonate alteration are host to gold mineralization, regardless of the degree to which the carbonatized rock has been subsequently deformed, or cut by quartz-carbonate veins of metamorphic origin.

Conversely, gold abundances of lithologies proximal to mineable concentrations of gold, range up to 1000 ppb (Figure 17). A threshold of approximately 5 ppb is recommended.

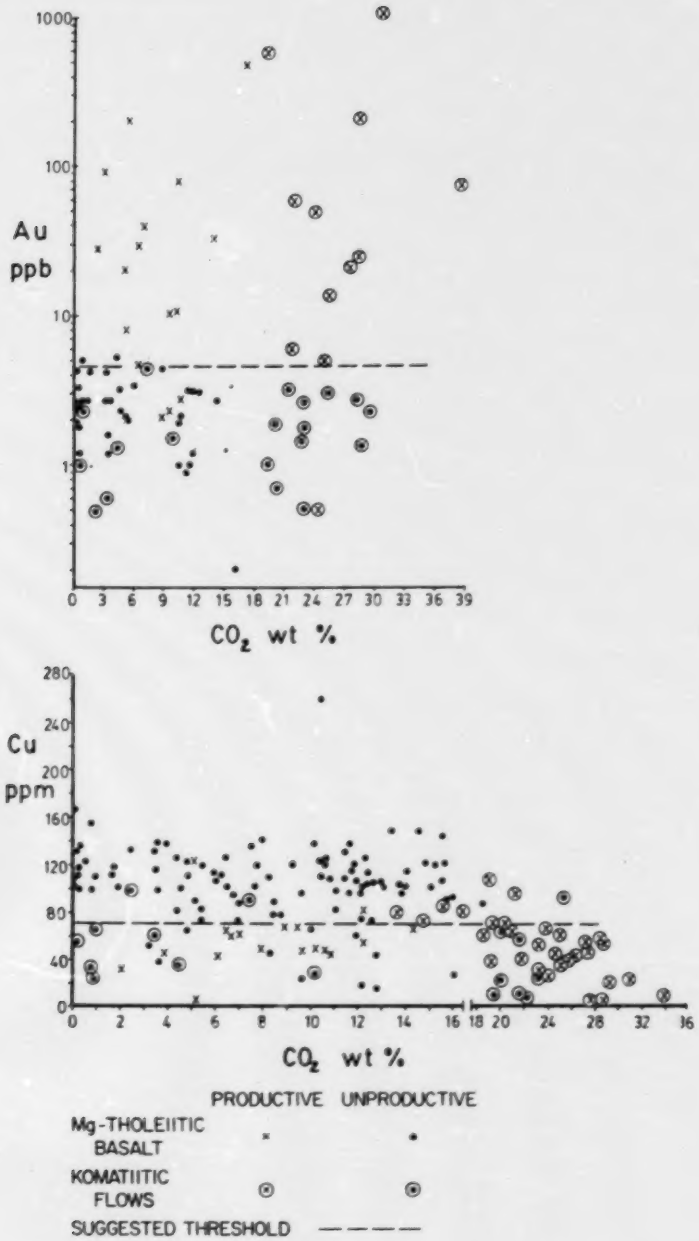
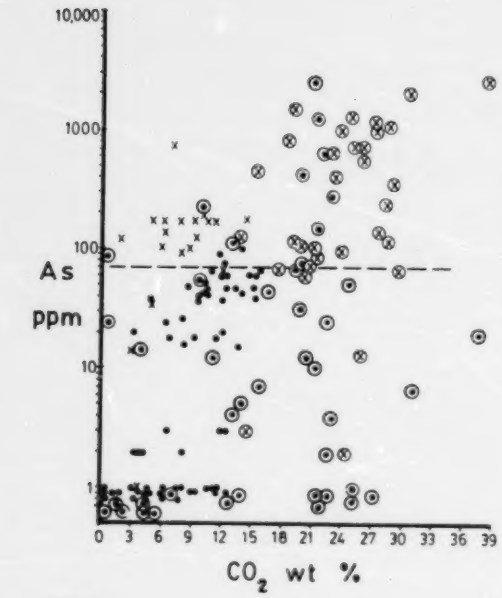
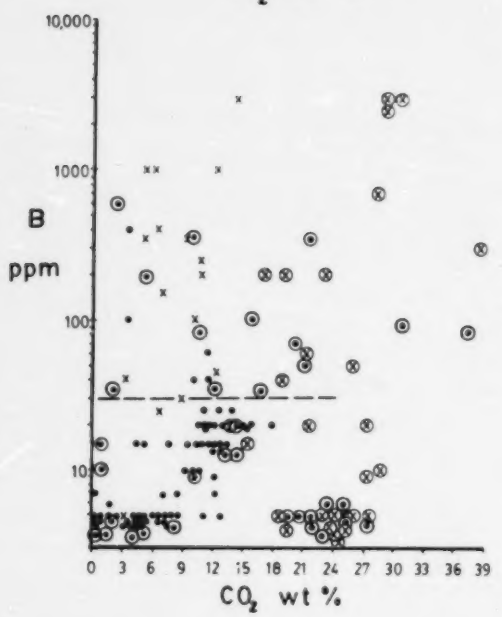


Figure 17–Abundances of arsenic (As), gold (Au), boron (B), and copper (Cu





in 'productive' and 'unproductive' Mg-tholeiitic basalts and ultramafic komatiitic flows.

Boron

Most unproductive basalts contain less than 30 ppm boron. In general, the productive Mg-tholeiitic basalts contain in excess of 30 ppm boron and one sample carries nearly 3000 ppm boron. A threshold of 30 ppm is recommended (Figure 17).

Boron content of the komatiitic flows cannot be used to discriminate between productive and unproductive groups.

Antimony

Background antimony abundances for unproductive Mg-tholeiitic basalts range up to 0.8 ppm, and 90 percent of the unproductive samples contain less than 0.35 ppm, the recommended threshold (Figure 18).

For the altered komatiitic flows, an antimony threshold of 1 ppm permits discrimination between the productive and unproductive groups. Approximately 70 percent of the productive komatiites exceed this threshold, whereas 80 percent of the unproductive komatiites contain less than 1 ppm Sb.

Copper

Unlike the elements which are enriched in the metalliferous alteration zones, copper has been leached from the productive basaltic flows (*see* Figure 17). A copper threshold of 70 ppm is recommended. No copper threshold permits discrimination between productive and unproductive komatiitic flows.

Lithium

Lithium can be used to discriminate between productive and unproductive Mg-tholeiitic basalts using a threshold of approximately 35 ppm (Figure 18).

The komatiites are enriched in lithium regardless of their proximity to economic gold mineralization or alteration intensity. Consequently, lithium abundance in komatiitic flows is not useful as a gold pathfinder element in the Timmins area.

Lead

Lead abundance in altered komatiitic volcanic rocks offers potential as a means to discriminate between productive and unproductive groups (Figure 18). Approximately 85 percent of the unproductive komatiites contain less than 10 ppm lead, whereas only 65 percent of the productive komatiites exceed 10

ppm. Although a significant percentage (35 percent) of the productive komatiites contain 10 ppm or less lead, it is apparent that carbonate alteration zones in komatiites having possible economic significance may be indicated by lead abundances in excess of 10 ppm.

Altered productive and unproductive Mg-tholeiitic basalts have indistinguishable lead abundances.

Sulphur

Pyrite is an accessory phase in all rocks in the Timmins area regardless of the degree of rock alteration; consequently, discrimination between productive and unproductive groups using sulphur content is less effective (Figure 18), because of the considerable range in sulphur contents of productive and unproductive lithologies. Group discrimination using sulphur is not recommended.

Carbon Dioxide

The frequency distribution of CO_2 weight percent in altered rock samples (Figure 19) indicates that productive and unproductive samples have the same range of CO_2 content. Because the sample population is biased to ensure representation of all alteration facies, the mean CO_2 content has little significance.

It has been argued that CO_2 abundance can be used as a guide to gold mineralization (Karvinen 1976, 1978a; Whitehead, Cameron, and Davies 1979; Whitehead, Cameron, and Davies 1980). The similarity between the ranges of CO_2 abundances in productive and unproductive rocks support the empirical observation that not all zones of carbonatized rock are associated with gold mineralization, a fact recognized by Burrows (1924) and Dunbar (1948). Hence, CO_2 abundance can be used only to identify and outline the carbonate alteration zones, which are in fact easily recognizable in the field. Other tests must be applied to discriminate between the barren and metalliferous carbonate alteration zones.

Zinc

Neither carbonate alteration intensity nor proximity to gold mineralization affect the zinc abundance in Mg-tholeiitic basalts or komatiitic flows (Figure 20).

Silver

Silver has been a byproduct from most of the mines in the Porcupine Camp, and the average gold-silver ratio for the mines of Tisdale Township is about 5 to

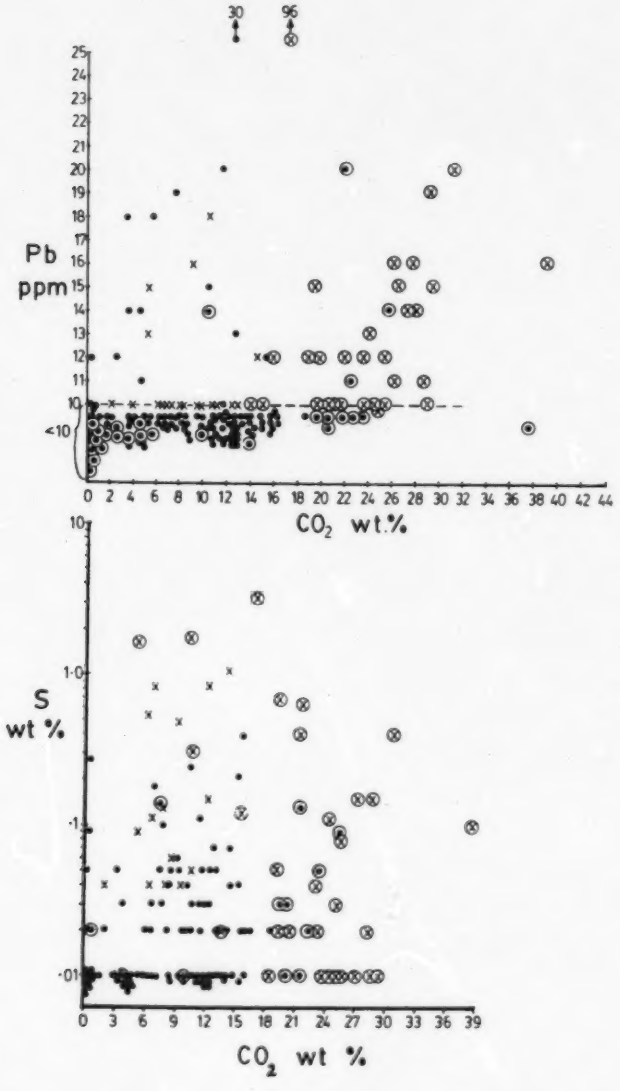
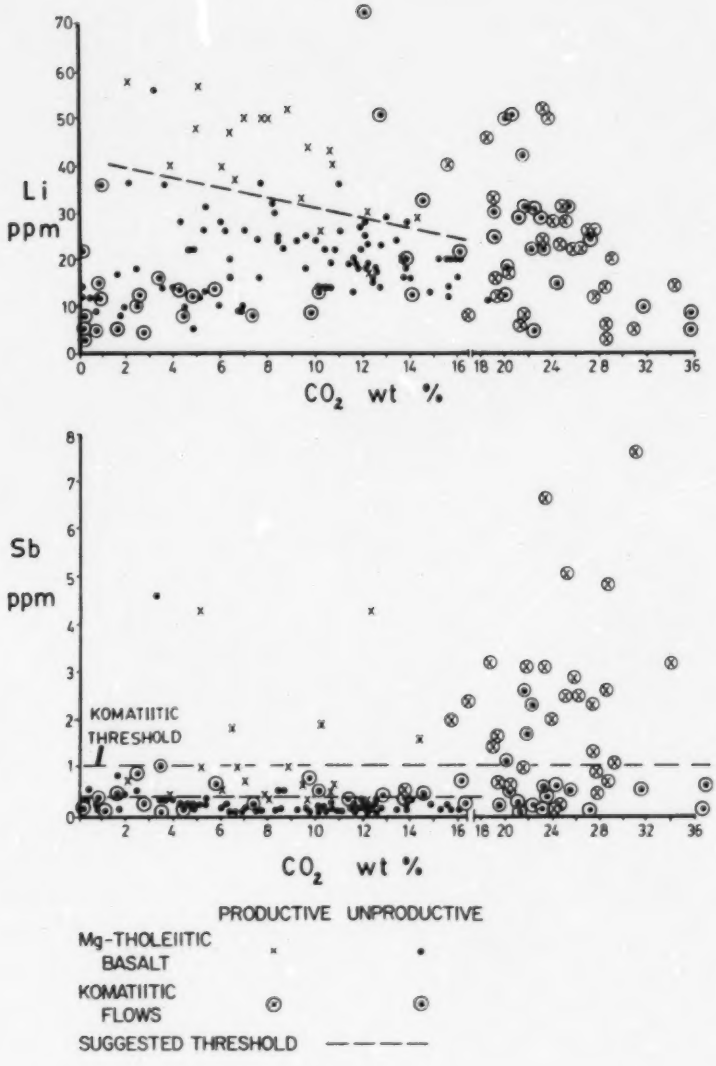


Figure 18–Abundances of lithium (Li), lead (Pb), antimony (Sb), and sulphur (S)



in 'productive' and 'unproductive' Mg-tholeiitic basalts and ultramafic komatiitic flows.

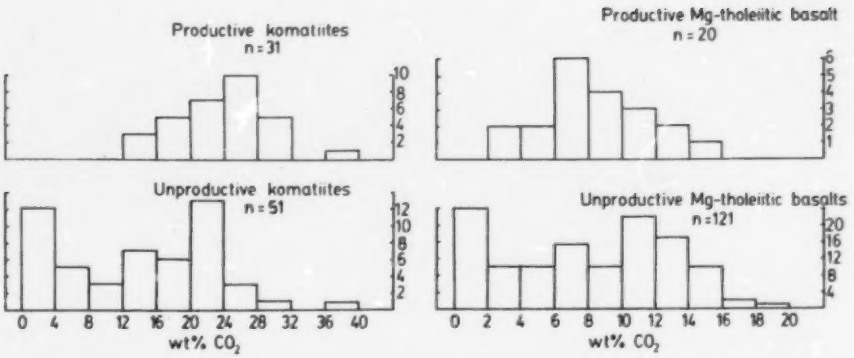

Productive komatiites
n = 31
Productive Mg-tholeiitic basalt
n = 20
Unproductive komatiites
n = 51
Unproductive Mg-tholeiitic basalts
n = 121
0 4 8 12 16 20 24 28 32 36 40
wt% CO2
0 2 4 6 8 10 12 14 16 18 20
wt% CO2

Figure 19–Comparison of carbon dioxide abundances in carbonatized magnesium tholeiitic basalts and ultramafic komatiitic flows which are proximal (productive) and distal (barren) to gold mineralization.

1 (Ferguson *et al.* 1968). At the 1 ppm detection limit, however, the silver has not been enriched in either the productive Mg-tholeiitic basalts or the komatiitic flows. In fact, virtually all samples contain less than 1 ppm silver (Figure 20).

Bismuth

Although no unproductive Mg-tholeiitic basalts contain an excess of 0.1 ppm bismuth (Figure 20), only 47 percent of the productive basalt samples exceed this value. Hence, bismuth does not reliably discriminate between the altered basalt populations.

Approximately 63 percent of the productive komatiites exceed the 0.1 ppm detection limit (Figure 20), whereas only 12 percent of the unproductive komatiites exceed this value. This is a relatively poor discrimination compared to that achieved using gold or arsenic.

Arsenic-Gold

To minimize the influence of a geochemical "flier", it is recommended that multi-element screens be used. Such a binary element function is illustrated on Figure 20. The threshold can be manipulated to yield the most effective results for a given deposit type in a specified area.

Application of the Lithogeochemical Screens

Application of the trace element geochemical screens is illustrated using the surface exposure of the Delnite Mine (Pamour #3) ore zones (*see* Figure 12). Additional examples are given by J.A. Fyon (1980a).

Gold, arsenic, antimony, and sulphur (Figure 21) outline the two Delnite Mine (Pamour #3) ore-zones exposed on surface. However, CO_2 abundances only identify the carbonatized rock. Note also, that the highest CO_2 peaks (> 20 weight percent) correspond to carbonatized, ultramafic, komatiitic flows and not to the surface limits of the ore-bearing magnesium tholeiitic basalt flows. Although sulphur clearly defines part of the ore-bearing units, it must be emphasized that within the two study-areas, rocks from barren and metalliferous carbonate alteration zones have similar sulphur ranges which render sulphur less useful as a geochemical screen.

Scale of the Dispersion Halo

The areal extent of the primary dispersion halo is also exemplified in Figure 21. Although the gold, arsenic, antimony, and sulphur profiles clearly define the upper and lower limits of the ore zones, the dispersion halo does not extend into either the footwall or hanging wall rocks. That is, the lithogeochemical target is no wider than the ore-bearing basaltic flow unit. Such restricted dispersion haloes define excellent drill targets, although the likelihood of locating such a restricted zone during a systematic, semi-regional, lithogeochemical sampling program is remote. Alternatively, if regional sampling programs could be focused on the collection of hydrated and carbonatized rock, both of which are relatively easy to recognize in the field, it is likely that samples would have been collected from the ore-zones.

CONCLUSIONS

1) Discrete, discordant, and stratabound zones of carbonate alteration occur in Formations IV and V of the Tisdale Group and in Formations II and III of the Deloro Group. In the core of an alteration zone, basaltic and ultramafic rocks consist of carbonate, quartz, and albite with traces of chlorite and sericite. This alteration facies is enveloped by an outer chlorite (in basalts) or talc-tremolite (in ultramafic flows) assemblage. Both calcite and dolomite can occur in the core zone, although when both are found in the same alteration zone, the calcite subfacies envelopes the dolomite subfacies.

2) The carbonate alteration and related hydration assemblages are superimposed upon an earlier palagonite and clay(?) - chalcedony - zeolite(?) calcite assemblage which respectively replace hyaloclastite granules and fill vesicles. The carbonate alteration, however, predates the earliest regional metamorphic event and locally was even synvolcanic.

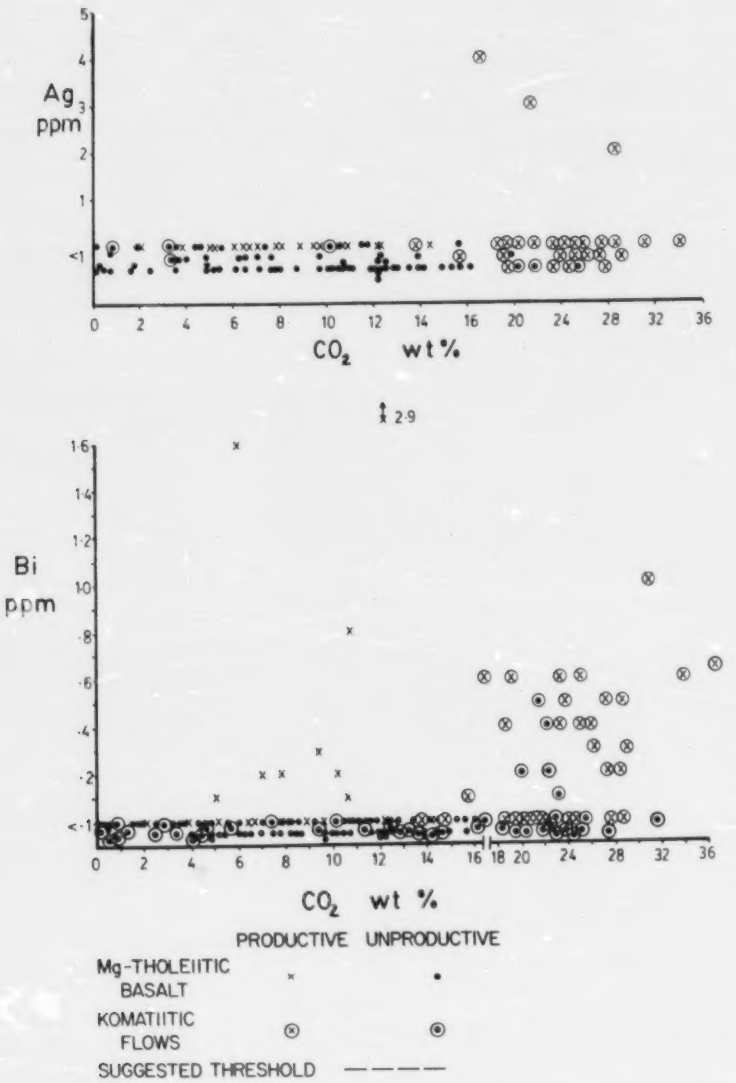
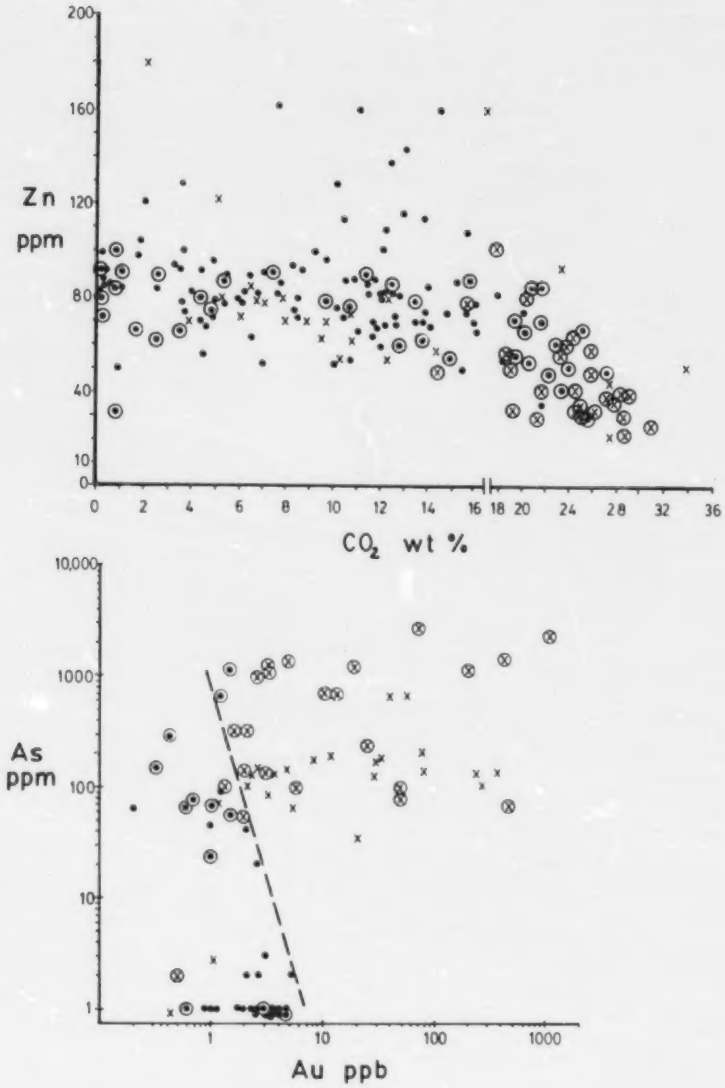


Figure 20–Abundances of zinc, silver, and bismuth in unproductive ar



xductive samples, including a gold-arsenic discriminant plot.

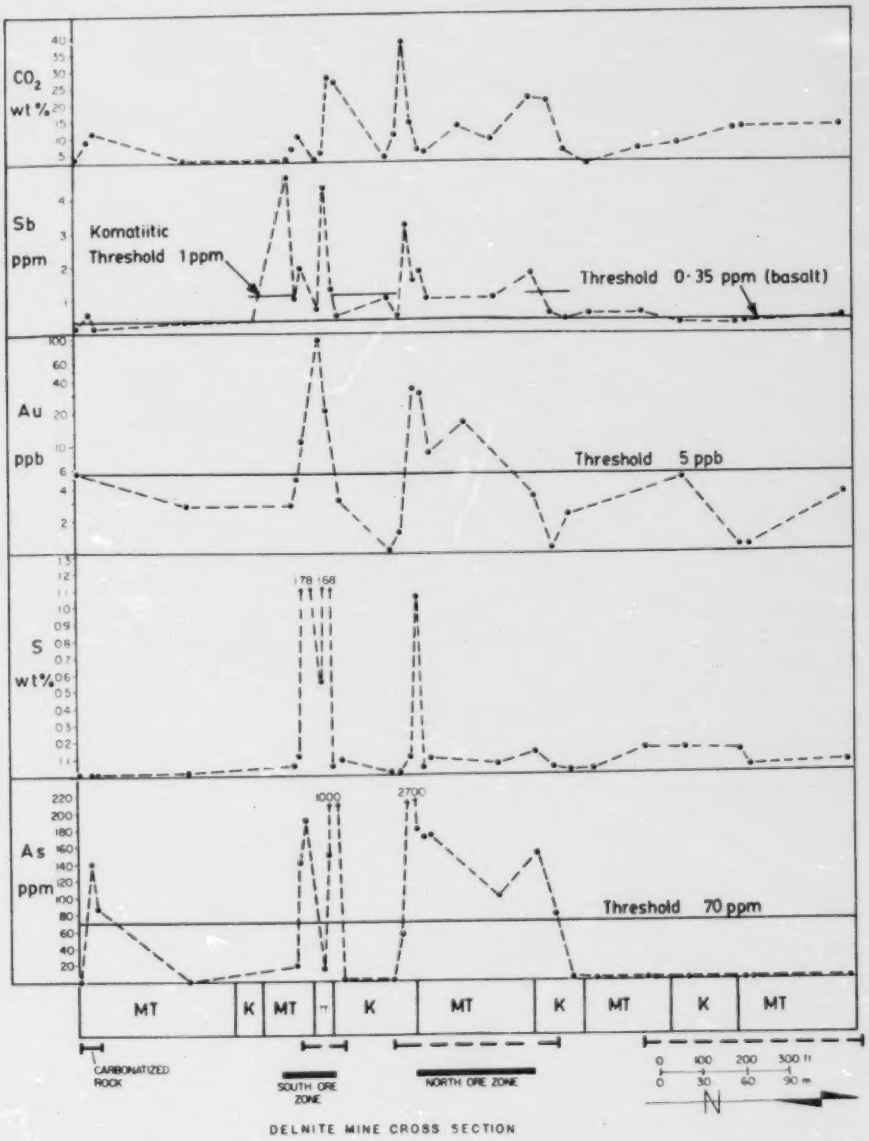


Figure 21–Section across the Delnite Mine (Pamour #3) surface exposure illustrating the location of carbonatized rock and the two ore zones. The carbon dioxide, antimony, gold, sulphur, and arsenic profiles are based on samples collected from the rock types present.

3) The carbonate alteration took place in a subsea floor environment and a sea floor environment. Carbonate alteration zones which developed in a subsea floor environment have the following characteristics:

a) The zones occur within a volcanic terrain which built up continuously and monotonously without major volcanic hiatuses;

b) These terrains lack large volumes of felsic volcanic or hypabyssal rock

c) In the vertical dimension, the limits of the alteration zones do not terminate abruptly at a major lithological contact;

d) Little gold has been won from this alteration environment.

Sea floor alteration zones have the following characteristics:

a) The zones occur within a diverse lithological sequence consisting of ultramafic (komatiitic) and tholeiitic flows proximal to small felsic volcanic centres (quartz-feldspar porphyries);

b) The carbonate alteration is restricted to one lithological sequence which is overlain by carbonate-free volcanic rocks of similar chemical composition;

c) The stratiform, gold ore (cherty dolomites or pyritiferous graphite) is restricted stratigraphically to the altered rock sequence, although the auriferous sediments may overlie relatively unaltered rock;

d) The stratiform gold ore is found in proximity to the quartz-feldspar porphyry bodies, although the auriferous sediments can be traced for 1 or 2 km laterally away from the porphyry complexes;

4) Geochemical (Li, B, oxygen-18 isotope, K_2O), petrographic, and morphological characteristics of the carbonatized rock suggest that the carbonate alteration zones developed by reaction of the volcanic rock with modified, sea water hydrothermal fluids.

5) The CO_2 content of the altered rock can outline the limits of the carbonate alteration zones; however, additional geochemical and geological screens must be employed to discriminate between the barren and the metalliferous alteration zones.

6) Zones of carbonatized Mg-tholeiitic basalt which host gold mineralization are discriminated from the numerous "barren" alteration zones using the following trace element screens: antimony (>0.35 ppm), arsenic (>70 ppm), boron (>30 ppm), copper (<70 ppm), gold (>5 ppb), and lithium (>30 ppm).

7) Carbonatized ultramafic komatiitic flows proximal to syngenetic gold mineralization are enriched in arsenic (>70 ppm), gold (>5 ppb), lead (>10 ppm) and antimony (>1 ppm).

8) The primary dispersion halo, outlined by the trace element screens, is limited to the flow unit in which the stratiform ores occur and averages only 30 m in thickness.

9) In the Porcupine Camp, unmineralized, ultramafic komatiitic flows have typical gold abundances of 1 to 5 ppb, similar to other Archean mafic and ultramafic rock types. These ultramafic flows are carbonatized with apparent, relative ease (Pyke 1975b, 1982) during which gold could be leached (Keays 1979). Carbonatized ultramafic rock must be considered as a favourable, although not necessarily an essential constituent of a favourable geological-hydrothermal environment.

10) All major gold producers in the northeastern part of the Abitibi Greenstone Belt lie within 10 km of the Destor-Porcupine, Larder Lake, and Kirkland Lake Fault Zones (*compare with* Gordon 1977). These regional structures are interpreted as fundamental fracture systems in the Early Precambrian crust (Pyke 1981, 1982), which are possibly analogous to graben structures (Jensen 1981) or modern oceanic rift systems, and through which sea water gained access to the Archean oceanic lithosphere. Regional exploration should focus on these major, east-west fault zones.

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20 Victoria Street
Toronto, Ontario M5C 2N8
Tel.: (416) 362-5211
Toll Free: 1-800-387-2689
Fax: (416) 362-6161
Email: info@micromedia.on.ca